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Water Filtration at Duluth

Duluth Water and Gas Dept., MN

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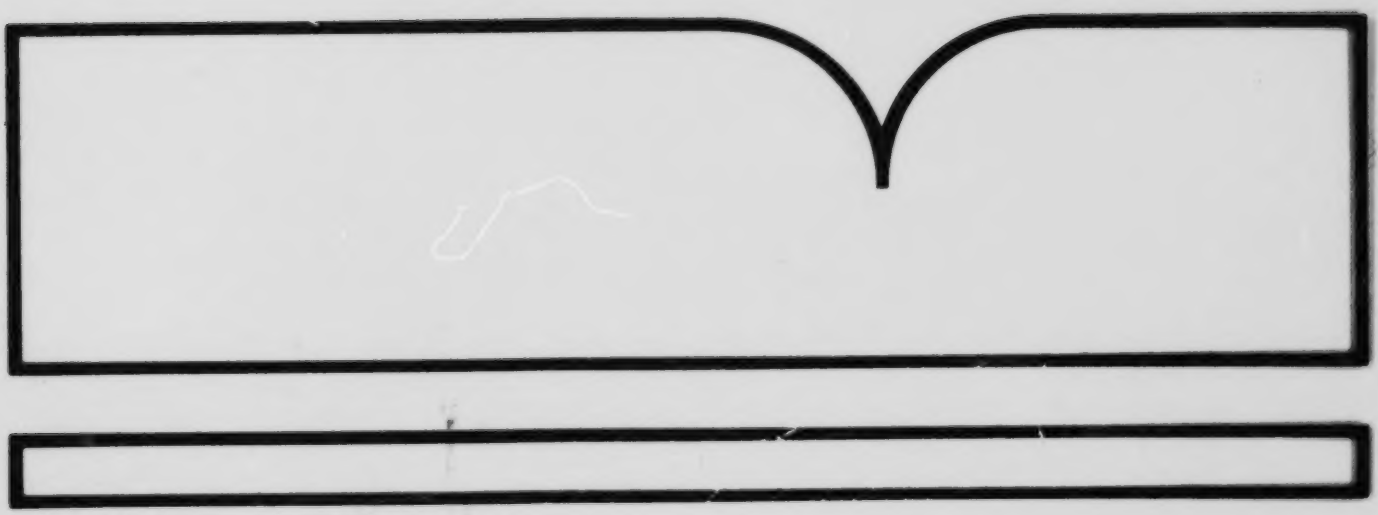

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WATER FILTRATION AT DULUTH

by

Frank X. Schleppenbach
Duluth Water and Gas Department
Duluth, MN 55802

Grant No. S-804221

Project Officer

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Office of Drinking Water
Washington, DC 20460

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16. ABSTRACT

After partial completion of the Lakewood Filtration Plant at Duluth, studies were begun with funding provided by the demonstration grant. Research covered a variety of topics and was done with a 10 gpm pilot plant located at the filtration plant, with the full scale plant operating at 20 MGD and 30 MGD, and in portions of the water distribution system. Water treatment plant sludge disposal also was studied.

An extensive program of raw and filtered water quality monitoring was conducted. The treatment plant was able to produce water with less than 0.1×10^6 amphibole fibers per liter and turbidity below 0.10 ntu on a routine basis, even when storms occurred. Filtration rate increases sometimes resulted in higher fiber counts in treated water, but the quality deteriorations were brief, generally lasting less than 20 minutes.

Monitoring techniques evaluated at Duluth included the transmission electron microscope for fiber counting, x-ray diffraction for amphibole mass, two types of particle counters, and two turbidimeters. Chemical treatment aspects studied included the effect of point of fluoride addition on alum coagulation and the use of inhibitors to control corrosion that occurred after alum coagulation was undertaken.

Natural freezing was found to be a very effective means of dewatering alum sludge. The rate of freezing could be related to freezing degree days, or degrees below 32° F X days.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and for minimizing the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report reviews the performance of Duluth's Lakewood Filtration Plant. Partial funding for construction and evaluation of this plant was provided by Demonstration Grant S-804221. Water quality and operating data for this report were obtained from January, 1977 until spring, 1982. The primary emphasis of this study was to demonstrate the capability of water filtration to remove asbestos fibers and turbidity-causing particulates from drinking water.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

After partial completion of the Lakewood Filtration Plant at Duluth, studies were begun with funding provided by the demonstration grant. Research covered a variety of topics and was done with a 10 gpm pilot plant located at the filtration plant, with the full scale plant operating at 20 MGD and 30 MGD, and in portions of the water distribution system. Water treatment plant sludge disposal also was studied.

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Natural freezing was found to be a very effective means of dewatering alum sludge. The rate of freezing could be related to freezing degree days, or degrees below 32^{o} F X days.

This report was submitted in fulfillment of Grant No. S-804221 by the City of Duluth under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from November, 1976 to May, 1982, and work was completed as of July, 1983.

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SECTION I

INTRODUCTION AND BACKGROUND

The presence of asbestiform fibers in the drinking water of communities using western Lake Superior as a water source became known in the summer of 1973, as a result of investigations performed at EPA's Environmental Research Laboratory at Duluth.[1]

In the fall and early winter of that year, an interagency agreement for studies of the problem was formulated and signed by the EPA and the U. S. Army Corps of Engineers. Under this agreement, EPA funded the pilot plant research on asbestiform fiber removal and the Corps funded a study of alternative water sources and sites for construction of a filtration plant or plants for the Duluth-Cloquet-Superior area. The Corps also managed the contract with Black & Veatch for the entire study, and the EPA provided technical assistance on the filtration research.

The pilot plant research was conducted at the Lakewood pumping station in Duluth, Minnesota, with the assistance of the Department of Water and Gas of the City of Duluth during the period from April through September 1974. In this time, a total of 227 granular media and 228 diatomaceous earth (DE) filter runs were performed.

The two principal objectives of the research were (1) to obtain information on asbestiform fiber removal and (2) to operate pilot plants in such a way as to generate data for engineering design and cost estimates.

Conclusions related to design and cost factors have been given by Robinson et al.[2] A paper on DE filtration optimization has been presented by Baumann.[3] EPA published the results of the pilot plant study.[4] Logsdon and Symons published an analysis of the pilot plant performance data.[5]

To learn how to reduce the asbestiform fiber count by filtration, a number of variables were studied. Those common to both granular and DE filtration were filtration rate, seasonal conditions, and raw water turbidity. Other important variables in the granular filtration study were filtration with and without sedimentation, dual media vs mixed (tri-) media, doses and combinations of inorganic salts and organic polymers, single-stage vs multi-stage flash mixing, and flash-mix chambers vs in-line mixers. Variables important in the DE study were one-step vs two-step precoating, vacuum vs pressure filtration, DE conditioning with alum or polymers, and body feed doses.

After the pilot plant research was completed, the City of Duluth

hired Black & Veatch to prepare an engineering report on the design of a filtration plant. The consultant recommended building a gravity, granular media filtration plant with mixed media (tri-media) filters. In February, 1975 City Council approved the report and authorized Black & Veatch to prepare plans and specifications for a 30 mgd plant.[6] This was done during the spring and summer of 1975.

The City of Duluth worked through the Minnesota congressional delegation in attempts to obtain a demonstration grant for water filtration. The efforts were successful, and EPA awarded a $4,000,000 demonstration grant on October 16, 1975 (retroactive to June 27 of that year). This has been described by Peterson.[7]

The demonstration grant application was reviewed by the Demonstration Grant Subcommittee of the National Drinking Water Advisory Council. Acting on the advice of an eminent filtration engineer, this group made the following recommendations:

"It is recommended that:

(1) The grant application in the amount of $4,000,000 be approved with the stipulations recommended under (2) and (3) below.

(2) Conditions be included in the grant offer which provide for and insure obtaining the maximum amount of good research data over a specified time frame on the removal of asbestos and on other research applications which would be beneficial to the water supply industry in providing safe water to the public.

(3) The conditions referred to in (2) above include: (1) a specific protocol developed with the advice of EPA Legal Counsel to cover evaluation procedures and plant operation procedures and schedules which will facilitate the research objectives when the plant is in operation and (b) specific provisions which establish how research talent will be provided to carry out the research and the evaluation process."

The recommendations strongly influenced the grant conditions that EPA specified when the project was funded. Region V monitored construction progress. In addition, the Drinking Water Research Division has had one engineer monitor the research and act as an advisor to the Duluth Department of Water and Gas since the grant was funded.

Construction progress was unusually rapid. Ground was broken in August, 1975. The plant dedication ceremony was held in 1976 at the end of November. Construction management techniques have been described by both Patton[6] and Peterson.[7] The filtration plant dedicated in 1976 was a direct filtration plant providing rapid mixing and filtration. A basin used as a chlorine contact basin until November 1976 was converted for use as a flocculation and sedimentation basin. The rebuilt basin was completed and put into use in the process flow stream in June, 1977.

Patton described the plant in detail.[6] A flow diagram for the plant is shown in Figure 1.

The design of the Duluth Water Treatment facility included three lagoons for sludge thickening and storage. It had been thought that static freezing during one winter cycle would be adequate to thicken the sludge enough for hauling to a landfill in the summer months. The first winter operation indicated that this probably would have been satisfactory. However, the Minnesota Pollution Control Agency's stringent requirements dealing with the ultimate disposal of asbestiform fiber laden sludge made it necessary to develop lagoon operating procedures that would maximize sludge volume reduction. A research project was planned to accomplish this goal.

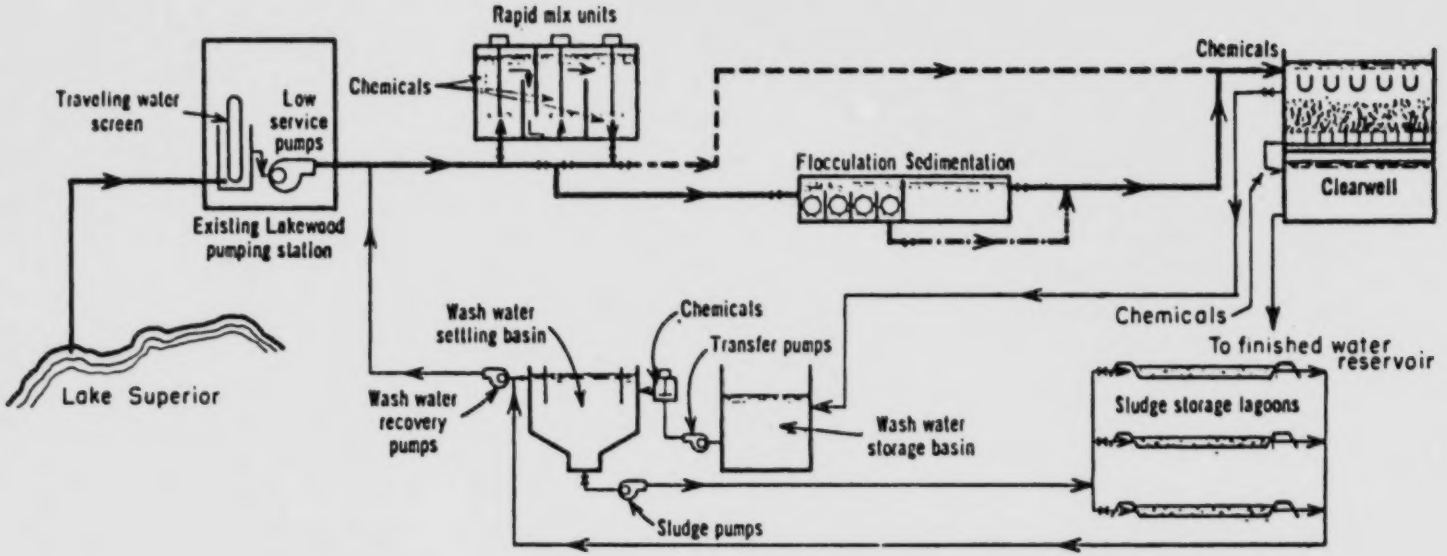


Figure 1. Flow Diagram for Filtration Plant at Duluth

SECTION II

CONCLUSIONS

RAW WATER

Asbestos

Although original pilot plant research indicated that both amphibole and chyrsotile asbestos fibers existed in Lake Superior, the work performed under this project indicates that only amphibole fibers are present.

The crysotile fibers found by the laboratory performing analysis for the original pilot plant research must have resulted from sample contamination. Raw water fiber counts were found in excess of 1 billion fibers per liter during stormy weather. The average fiber count of 171 samples taken from January 1977 to February 1981 was 69.8 million fibers per liter. Since the cessation of discharging taconite tailings into Lake Superior by Reserve Mining Company at Silver Bay, Minnesota, the fiber counts have declined to less than 10 million fibers per liter. Amphibole fiber counts ranged from a high of 1.2×10^9 to a low of 1.2×10^6 before the cessation of discharging the tailings.

Turbidity

Turbidity in Lake Superior raw water is usually less than 1.0 nephelometric turbidity unit (NTU) but can exceed 10 NTU during stormy weather. Although fiber counts increase with increased turbidity, a direct correlation between turbidity and fiber counts was not found.

Corrosivity

Lake Superior raw water is saturated with air and is a very soft water so rusty water problems did occur and were apparently aggravated by the treatment processes employed for asbestos removal.

FINISHED WATER

Asbestos Removal

The Duluth filtration plant has demonstrated successfully that asbestiform fibers can be removed from drinking water on a day-to-day basis. The effluent monitoring program has shown conclusively the dependability of the filtration process. Asbestos fiber counts have been consistently below 0.1×10^6 fibers per liter since the plant started operation.

Turbidity Removal

With proper chemical treatment filtered water turbidity can be reduced consistently to below 0.1 NTU and generally is 0.04 or 0.05 NTU.

This filter plant performs well under a number of adverse conditions. Turbidity levels considered objectionable or as a break-through condition here, would not be regarded as such in other filtration plants. The turbidity was rarely above 0.05 NTU and almost always less than 0.1 NTU, which is less than the AWWA goal for turbidity.

Bacteria Removal

In a previous investigation of treatment effectiveness during normal operation (chlorination, flocculation, and direct filtration in that order) no coliforms, and also no other bacteria remained viable after treatment.

While it is difficult to arrive at definite conclusions from the modest data presented here, the following assumptions can be made:

(1) Coliforms can be effectively removed from Lake Superior raw water containing low numbers of coliforms by flocculation and direct filtration without chlorination.

(2) Some other bacteria do pass through the filters, as indicated by the M-SPC counts.

Particle Counts

There is no direct correlation between the results from the HIAC particle counter and the results from the electron microscope analysis. The particle counter can be used as an indicator of water quality. Ninety percent of the samples with particle counts less than 1000 particles per 100 mL contained less than 20,000 amphibole fibers per liter. Since the particle counter gives a direct measurement of particulates present in the water, it is more useful than turbidity for evaluating water quality.

Corrosivity

Two corrosion control chemicals, Virchem 932 and sodium tripolyphosphate, have alleviated most of the rusty water problems in domestic galvanized iron piping. These phosphates interfere with filter set up if they are in the backwash water so they are not fed for 45 minutes to an hour before a backwash.

Backwash Sludge Considerations

The data gathered in this project indicate that with appropriate control the natural freezing of alum sludge is highly successful in reducing sludge volume. Static freezing in deep lagoons is not as efficient as in shallow lagoons. Freeze degree days can be determined from existing climatological data and can be used as a guideline to design lagoons for sludge volume reduction by natural freezing. During freezing weather, sludge should be delivered by spraying onto already formed ice.

DESIGN CONSIDERATIONS

Several modifications were made to the plant piping arrangements, instrumentation, and sludge facilities as a result of operational experience.

All sludge is distributed to the lagoons by spraying from the hydrants with nozzles. The lagoon inlet structures are not used. This solved a sludge distribution problem by giving even distribution of sludge and a smooth surface for winter freeze operation and snow removal.

The lagoon outlet structures were modified by sealing the stop log weirs and using siphon hoses for decant. This completely eliminated a short circuiting problem when sludge is pumped from the clarifier.

A taste and odor problem occurs each spring when water is to be decanted from the lagoons after the thaw. The sun reduces both taste and odor given enough time, however, HTH is added to speed up this process.

The automatic sludge pumping cycle has been abandoned. Sludge is pumped only when the operator is at the lagoon to observe it so that the pump can be stopped when sludge appears to be thin. This reduced volume pumped to lagoons by 90%.

The sludge collector in the clarifier is run continuously which promotes sludge thickening and reduces the sludge volume pumped to the lagoons.

The decant return line from the lagoons was repiped to discharge into the transfer storage basin rather than the return pit. This change made it possible to better treat the decant water in the clarifier before returning it to the head of the filter plant.

A line with valves was added from the sludge pump discharge to the transfer storage basin eliminating the need to drain the clarifier into the lagoons when the clarifier is cleaned.

A line was added with valves from the sludge pump discharge to the return line to the head of the filter plant. When the sedimentation basin is cleaned now, the clear decant can be returned to the head of the plant for treatment instead of pumping it to the lagoons or to the wash water recovery basin.

Operational pH is temperature dependent so a temperature probe was installed with readout in the control room. Also an in-line pH monitor was installed with control room readout for alum feed monitoring.

An in-line turbidimeter was installed in the high lift pump discharge to monitor the composite plant effluent.

An in-line chlorine monitor was installed with control room display for

safety and economic reasons.

The chlorine injection point was moved from the rapid mix effluent to rapid mix chamber #1 to eliminate a change in pH after the coagulant is added.

Sodium hydroxide application was moved to rapid mix #1 for pH control.

Since fluoride complexes alum, it was moved from the filter influent flume to the filter effluent flume.

OPERATING CONSIDERATIONS

Water Temperature - Optimum pH

Optimum pH for fiber removal is dependent on raw water temperature and varies from 6.85 when the raw water is relatively warm to 7.35 when it is colder.

Alum Dose - Suspended Solids Removal

Alum dose varies with suspended solids and ranges from a minimum of 10 mg/L to 20 mg/L. Asbestiform fibers are the last solids to be removed in the process. The alum dose must satisfy all of the coagulant needs of the other incoming suspended solids before fibers will be removed.

Filter Stress

The various stress conditions studied did not have a continuous detrimental effect on the effluent quality of the filter plant. Changes occurred, but these were generally short term.

One operational change was made as a result of these stress studies. Filters are no longer shut down with a high headloss. If a filter has not reached the run termination headloss of 8.0 feet prior to plant shutdown, it is backwashed if the headloss is 7.5 feet or greater. This lessens the chance of a major breakthrough of flocculated materials when the plant is restarted.

SECTION III

RECOMMENDATIONS

This section of the report makes recommendations concerning additional research possibilities.

Determine the feasibility of an acid feed system to lower pH to optimum for fiber removal. At present an overdose of alum must be used.

Determine whether or not filtration of Lake Superior water really makes it more corrosive as it seems.

Determine optimum depth of lagoons when natural freezing of sludge under static conditions is to be used for volume reduction of summer produced sludge.

Research into insulating the sides of lagoons to prevent absorption of heat from the ground below frost line.

Research into heat generated by anaerobic digestion activity under ice cover. This activity tends to prevent or retard ice production.

Research into the economic aspects of labor expense to pump sludge from under ice cover as opposed to static freezing and hauling thickened sludge.

SECTION IV

SAMPLING AND ANALYSIS

SAMPLING PROCEDURES

Collection

Grab samples were taken during filter runs from the appropriate sample tap and analyses were performed on these samples. Certain tests with the particle counter were performed with its sensor connected directly to a filter effluent tap. Samples were taken from a sampling tap that exists on the bottom of the effluent pipe of each filter. This tap is located about ten (10) feet downstream from the filter effluent control valve. A 250 mL sample was taken for particle counting and a 500-1000 mL sample was taken for electron microscope analysis.

With the exception of the electron microscope fiber counting, the optical detection work by Diehl[12] and the X-RAY diffraction work, all of the laboratory tests were done at the Duluth Lakewood water treatment plant. For the electron microscopy, samples were filtered and grids prepared at the Lakewood plant and then the grids were taken either to the Environmental Protection Agency's laboratory or to the University of Minnesota Duluth laboratory for counting. For the optical detection work samples were taken and split, then half of the original was delivered to the University for optical detection of fibers and the other half was prepared for electron microscope counting.

Sample volumes for coliform tests were either 1,000 mL or 1,800 mL Sample volumes for total bacteria ranged from 1 mL to 100 mL, depending on the expected bacterial population.

Preservation

Since the samples were utilized within 24 hours of taking them, preservation was not necessary.

CHEMICAL ANALYSIS

General

Specific conductance, chlorides, phosphate, pH, sulfate, aluminum, alkalinity, zinc, fluoride, iron, dissolved oxygen, suspended solids, and sodium were analyzed in accordance with Standard Methods for the Examination of Water and Wastewater 14th Edition[14].

Polymer

Polymer concentrations were determined gravimetrically. Approximately 90 grams of polymer solution were added to a previously weighed container

and it was reweighed. The container holding the sample was then oven dried at 103-105°C for 24 hours and weighed again. Research has indicated that only 90% recovery is achieved, also there is a 0.006% solids content in the make up water. The percent polymer was then calculated from the weight of the sample incorporating the two adjustments mentioned.

MICROBIOLOGICAL ANALYSIS

Total Coliform Counts

Total coliforms were determined in accordance with Standard Methods for the Examination of Water and Wastewater, 14th Edition[14]. Colonies with a metallic green sheen were considered coliforms.

Total Bacteria Counts

Total bacteria counts were determined by the method of Geldreich and Taylor[13]. Total bacteria cultures were incubated at 20°C and 35°C for 72 hours.

TURBIDITY

Individual Samples

During the early stages of the research turbidity information on individual grab samples was determined using a bench Model 2100 A Hach turbidimeter. Since the effluent turbidities were frequently below the reliable lower detection limit of the 2100A, a Sigrist Photometer Model UP52B2 was purchased in October 1979 and it was used from then on.

Continuous Monitoring

All four filters and the raw water influent were monitored for operational turbidity using on-line turbidimeters, Hach Model 1720, which were calibrated using the bench model 2100A. The 2100A is calibrated using formazin standards.

Air bubbles interfered with turbidity readings for the pilot plant so those samples were degassed by heating before the turbidity was read.

PARTICLES AND ASBESTOS FIBERS

Particle Counter

Grab samples were taken from the filter plant effluent for each particle counter analysis.

The filter effluent is saturated with dissolved oxygen. If the samples were analyzed with the particle counter immediately after they were taken, the dissolved oxygen bubbles appeared as particles to the sensing unit. To eliminate this problem, the samples were heated to approximately 65°C to release the dissolved gases. They were then cooled to room temperature before being analyzed with the particle counter. This technique provided repeatable particle counts on samples taken simultaneously.

Optical Detector

For sampling and analysis by optical detector the reader is referred to Section 7 of reference twelve "Optical Detection of Fiber Particles in Water".

X-Ray Diffraction

Sampling and analysis for x-ray diffraction was performed in accordance with reference fifteen "Semi-Quantitative Determination of Asbestiform Mineral Concentrations in Western Lake Superior Water Samples, etc".

Transmission Electron Microscope

Determinations of asbestos fibers were made in accordance with the Environmental Protection Agency's "Interim Method for Asbestos" as described in memo from the Athens, Georgia EPA Laboratory's C.H. Anderson to Phil Cook (EPA, Duluth), Earl McFarren (EPA, Cincinnati), and Jim Millette (EPA, Cincinnati) dated July 30, 1976.

SECTION V

RESULTS AND DISCUSSION

WATER QUALITY MONITORING

Monitoring Results

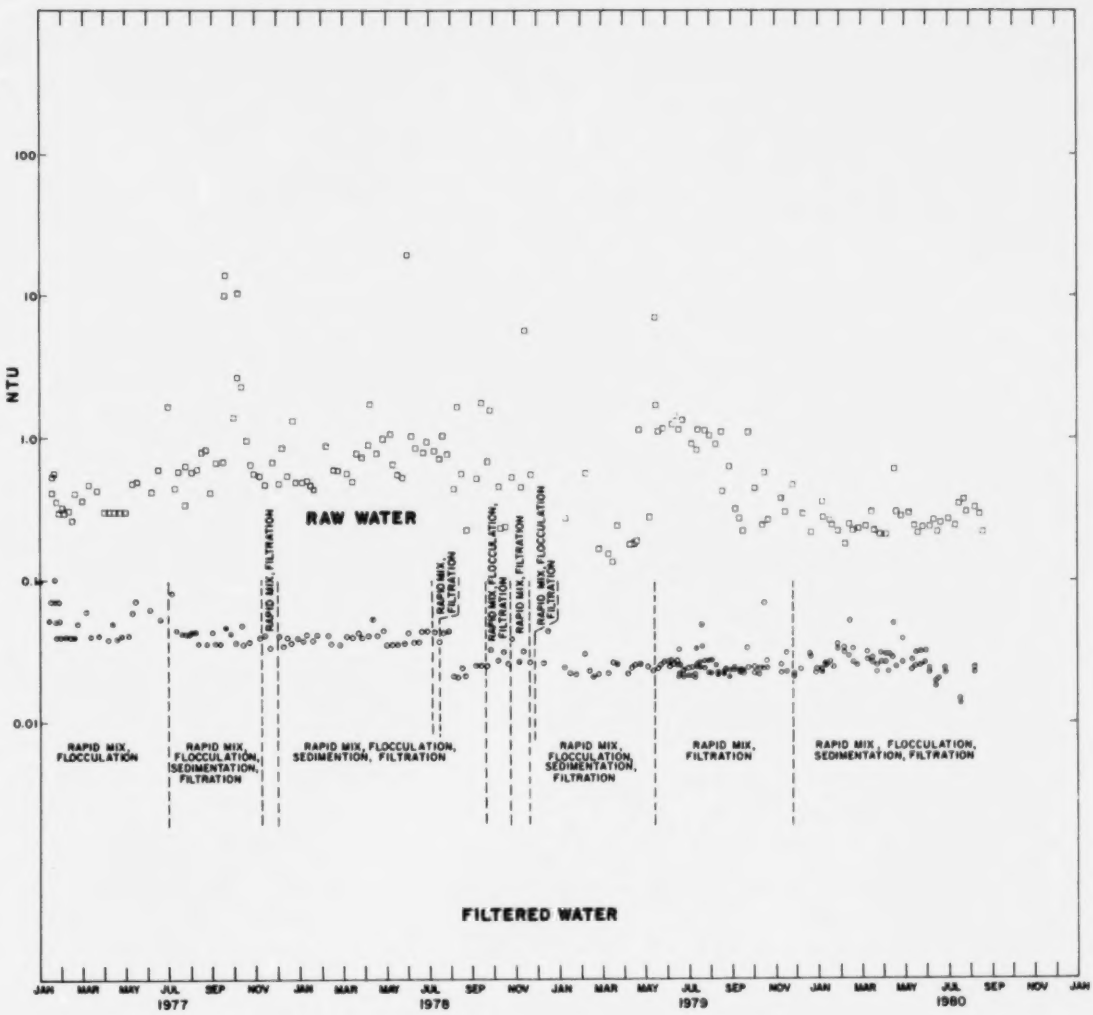
The Duluth filtration plant was built to remove asbestos fibers from Duluth drinking water. The water quality data collected since January, 1977 show that the plant performance has exceeded expectations. Raw and filtered amphibole fiber counts and turbidities are shown in Figure 2. Asbestos fiber counts have consistently been below 0.1×10^6 f/L since the plant started operation. Turbidity is kept below 0.1 NTU generally 0.04 or 0.05 NTU.

Asbestos fiber concentrations in filtered water were higher in January, 1977 than in later months. In fact, fiber counts through September, 1977 seem to be higher than subsequent counts. This trend may have occurred because as personnel gained experience in their jobs they improved plant operating techniques as well as electron microscope (EM) analysis techniques. Training operators in the finer points of plant operation at a specific plant might take a number of months. Also, eliminating little problems that usually occur in a totally new plant takes time. The detection limit for asbestos fibers decreased from 0.19×10^6 in January, 1977, to 0.067 in February, to 0.030 in May, and to 0.010×10^6 in September. The lower detection limit may have been caused by improved analytical skills, by production of water with fewer particulates (resulting in filtration of larger sample volumes for EM analysis) or by a combination of both factors.

Because progressive improvement in operating and analytical capabilities took place during the first year of operation, a comparison of direct filtration data and conventional treatment data should not be made with 1977 results. Determining how much improvement in water quality was caused by flocculation and sedimentation and how much was caused by the improvement of skills that occurred in the first nine months is not possible. Comparisons of treatment efficiency can be made after 1977 because both the plant staff and the laboratory staff were capable and experienced. Figure 2 presents data for this comparison.

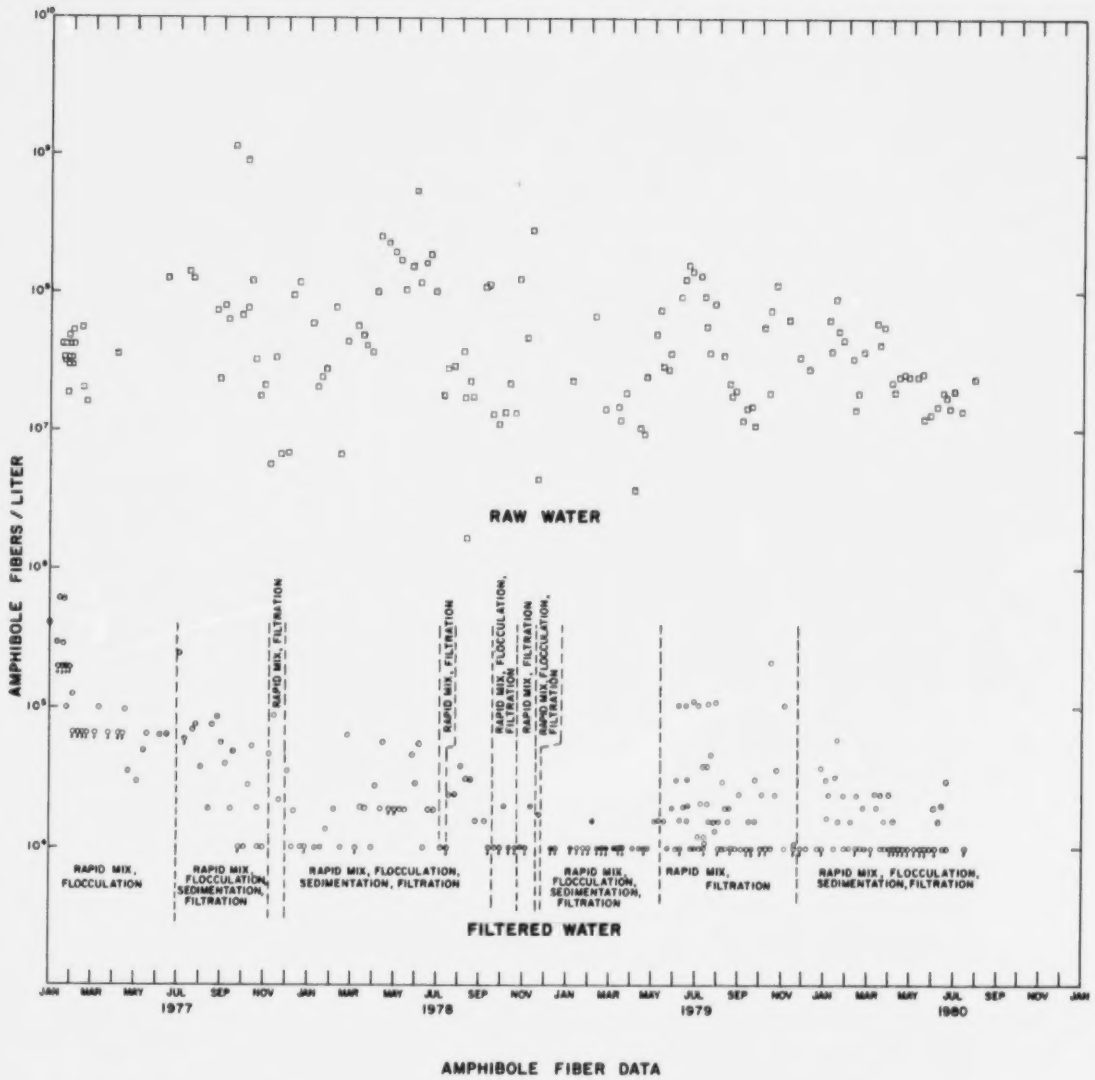
Evaluation of Fiber Counts vs. Turbidity

In the review and analysis of pilot plant data, Logsdon and Symons recommended that quality control for filter operation should be based upon producing finished water with a turbidity of not more than 0.10 NTU.[5] Filtered water turbidity and amphibole counts can not be directly correlated, because at turbidities below 0.1 NTU and at low fiber counts, the data obtained by either method could be approaching the detection limit for the method and thus reflecting the limit rather than an actual



TURBIDITY DATA

Fig. 2A, Water Quality monitoring results
Duluth filtration plant


AMPHIBOLE FIBERS / LITER
RAW WATER
FILTERED WATER
RAPID MIX, FLOCCULATION
RAPID MIX, FLOCCULATION, SEDIMENTATION, FILTRATION
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AMPHIBOLE FIBER DATA

Fig. 2B, Water Quality monitoring results
Duluth filtration plant

sample value. This has already been discussed with regard to asbestos. For turbidity, the detection limit may vary from 0.03 to 0.05 NTU at Duluth.

Because a comparison of turbidity vs. fiber counts would not be very useful, another approach has been taken. Data for fiber counts for filtered water at the Lakewood Filtration Plant (pilot plant data excluded) have been grouped according to turbidity and operating conditions. Most of the filtered water samples had turbidities less than 0.10 NTU. Fifteen samples from full scale tests of filter behavior during conditions of stress, such as rate changes, had turbidities ranging from 0.10 to 0.71 NTU.

The rate change operating conditions were: (1) increasing filtration rate by 33 percent when one filter is backwashed, (2) starting a clean filter after backwash, and (3) starting the entire plant after overnight shutdown. Monitoring data were collected during equilibrium operating conditions.

Probability plots were prepared from the three groups of data. Figure 3 shows the probability of observing a given amphibole fiber count when the filtered water turbidity is less than 0.10 NTU and when the turbidity equals or exceeds 0.10 NTU during rate change conditions. Amphibole counts are much higher for the higher turbidity data group. For the sample groups with turbidity below 0.10 NTU, fiber counts for monitoring data are about half the counts for samples taken during rate change tests, for any probability of occurrence.

Figure 3 reinforces the earlier recommendation to produce water not exceeding 0.1 NTU. Even though a turbidity reading can not be used to calculate a fiber count, keeping turbidity below 0.10 NTU at Duluth most of the time has resulted in producing water substantially lower in amphibole fibers than the water would have been if it had been produced merely to meet a 1 NTU turbidity MCL.

Results During Storms

In January, 1976, while the filter plant was being built, engineers from the Drinking Water Research Division and EPA Region V traveled to Duluth to discuss technical aspects of asbestos removal from Lake Superior water with the Duluth City Council. A key question discussed was fiber removal capability during periods of high turbidity. Raw water turbidity did not exceed 5 NTU during the five months of pilot plant operation, but during the fall of 1975 turbidity of unfiltered water in the distribution system had exceeded 10 NTU after a severe storm. Duluth citizens were worried about the quality of their drinking water, and City Council wanted to know if the filtration plant would be effective when raw water fiber counts were near 10^9 fibers per liter.

EPA engineers explained that no pilot plant data were available, but stated that on the basis of filtration experience and engineering

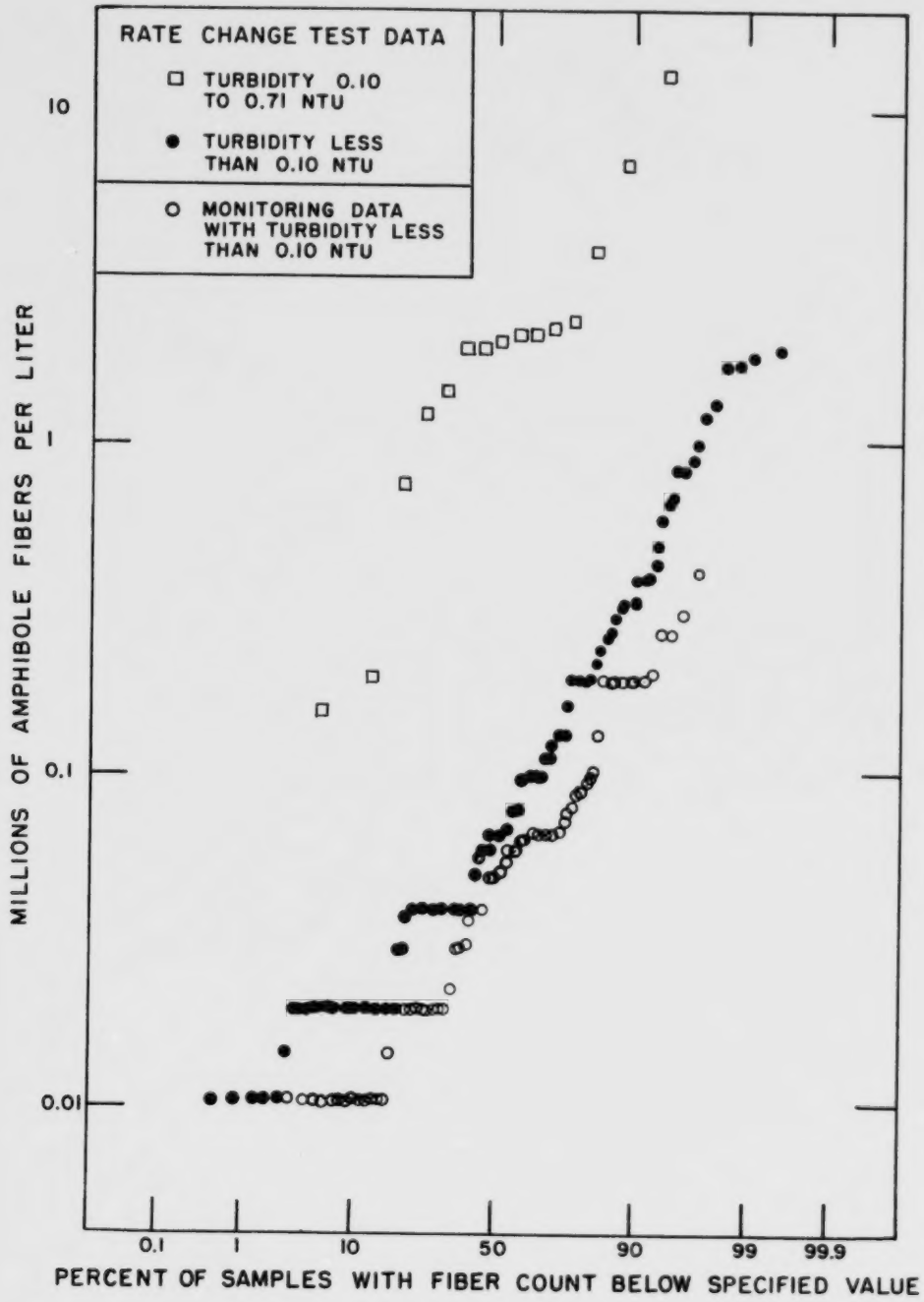

figure 3. Comparison of frequency distributions of fiber counts of filtered water sample groups. Lakewood Plant

Note: BDL values plotted at detection limit

data base for this figure— Jan. 1977 through Aug. 1978

judgment, good performance would be expected during storms.[8] Removal of particles is easier when particle counts are very high. For example, coagulation and sedimentation can be accomplished more easily in turbid water than in clear water.

In fall, 1977, storms on Lake Superior caused raw water turbidity and asbestos fiber count to increase sharply. The efficiency of the filtration plant was tested twice when amphibole fiber counts were very high, and on both occasions plant performance exceeded expectations and confirmed the soundness of the plant design and the capabilities of plant operating personnel. Data obtained during the storms are shown in Table I.

On September 19, the raw water turbidity reached a high of 15 NTU. A raw water sample (#203) was taken at 4:00 P.M. for electron microscope analysis. The sample was taken before the raw water turbidity peak occurred. A plant effluent sample (#202) was taken for electron microscope analysis one and one-quarter hours later (5:15 P.M.). The plant effluent turbidity reached the normal operating turbidity of 0.04 NTU at 6:30 P.M. The highest effluent turbidity experienced during the storm was 0.08 NTU prior to the chemical feed adjustments.

Because the detention time in the flocculation and sedimentation basins is between three and four hours and effluent sample number 202 was taken one and one-quarter hours after the raw water sample, water sampled as filter effluent had been taken from the lake 2 to 2-1/2 hours before the raw water was sampled. Water quality might have changed in that time interval, so plans were made to sample again during another storm condition to confirm the data of September 19.

The opportunity arose on October 8, when a storm caused the raw water turbidity to reach 11 NTU. A sample of the raw water (#213) was taken for electron microscope analysis at 8:30 P.M. At 12:00 A.M., or three and one-half hours later, a plant effluent sample (#212-2) was taken for electron microscope analysis. A plant effluent sample (#212-1) was also taken before any chemical feeds were adjusted for removal of the increased turbidity. The results confirmed the September finding and provided assurance that the plant is very effective for fiber removal during storms.

Distribution System Water Quality

Unfiltered water containing amphibole asbestos fibers was pumped into the distribution system for nearly twenty years. While the filtration plant was under construction, a program of water main flushing was carried out. Duluth has numerous water storage reservoirs in the distribution system. About three days' supply can be stored. This type of distribution system was developed in past years so that drinking water could be provided without pumping lake water when storms caused high turbidity.

TABLE I

PLANT PERFORMANCE DURING STORMS

Sample #203 - Raw Water 9-19

Volume filtered	3.0	mL
Turbidity	14.0	NTU
Detection limit	32	million fibers per liter
Fibers counted	37	amphibole
Grid-squares analyzed	1	
Amphibole fibers	1200	million fibers per liter

Sample #202 - Plant Effluent 9-19

Volume filtered	1000	mL
Turbidity	0.045	NTU
Detection limit	0.0096	million fibers per liter
Fibers counted	5	amphibole
Grid-squares analyzed	10	
Amphibole fibers	0.048	million fibers per liter

Sample #213 - Raw Water 10-8

Volume filtered	5.0	mL
Turbidity	11.0	NTU
Detection limit	19	million fibers per liter
Fibers counted	43	amphibole
Grid-squares analyzed	1	
Amphibole	830	million fibers per liter

Sample #212-2 - Plant Effluent 10-8

Volume filtered	994	mL
Turbidity	0.045	NTU
Detection limit	0.0097	million fibers per liter
Fibers counted	3	amphibole
Grid-squares analyzed	10	
Amphibole filters	0.029	million fibers per liter

Sample #212-1 - Plant Effluent 10-8

Volume filtered	1000	mL
Turbidity	0.05	NTU
Detection limit	0.0096	million fibers per liter
Fibers counted	12	amphibole
Grid-squares analyzed	10	
Amphibole fibers	0.12	million fibers per liter

Flushing the reservoirs has been done as a part of normal distribution system operation. When the filter plant operation started, a substantial reduction of fibers took place, from hundreds or tens of millions, to less than ten million. In March, 1977 amphibole fibers were generally less than 1×10^6 in the reservoirs. By June, 1978 amphibole fiber counts in the distribution system were similar to amphibole fiber counts of filtered water at the Lakewood plant. These results are summarized in Table II.

TABLE II

RESERVOIR AMPHIBOLE FIBER CONCENTRATIONS

Reservoir	Distance from Plant	2-11-77 10^6 f/L	3-10-77 10^6 f/L	3-17-77 10^6 f/L	3-22-77 10^6 f/L	10-25-77 10^6 f/L	6-08-78 10^6 f/L	8-29-79 10^6 f/L
"A"	Nearest	0.61	N.T.	0.36	0.32	0.15	BDL (0.032)	0.50
Endion		1.8	0.21	0.11	3.0	0.27	N.C.	BDL(0.019)
Woodland		3.4	0.21	0.16	(BDL (0.48)	BDL (0.87)	0.024	N.C.
Highland		N.T.	1.2	1.3	1.3	BDL (0.12)	N.C.	0.12
Middle		9.7	N.T.	0.50	0.50	1.2	0.048	N.T.
West Duluth	Farthest	4.4	0.42	N.T.	0.48	1.4	N.C.	0.019

N.T. - no sample taken

BDL - below detectable limits (detection limit in parentheses)

N.C. - sample could not be counted because of excessive debris

CHEMICAL CONDITIONING OF WATER

Polymers and Fibers

When the pilot plant research was conducted in 1974, the EM laboratory, Ontario Research Foundation (ORF), reported both amphibole and chrysotile asbestos fibers in Lake Superior water. This finding was disputed by Dr. Cook at EPA's Environmental Research Laboratory in Duluth. Two additional problems existed with ORF data: the amphibole counts were much lower than the results of other laboratories, and long delays (4 to 8 weeks) occurred between sample collection and receipt of EM data. The dilemma was exacerbated because EM analysis for asbestos fibers in water was in its infancy, EPA was involved in a court case related to fibers in Lake Superior, and the pilot plant study was originally planned to be only four months long. Changing EM laboratories in the middle of the project would necessitate throwing out all the ORF asbestos data.

The EPA project officer for pilot plant research, Dr. Logsdon, decided to continue to use the Ontario Research Foundation rather than begin anew. In spite of the difficulties, the ORF results did show that certain granular media and diatomite filtration processes were very effective for amphibole fiber removal. These results were substantiated by amphibole mass determinations made in Dr. Cook's laboratory.

In order to resolve the chrysotile problem, Black & Veatch discussed the matter with ORF and received assurances that their data were good, in the professional opinion of ORF scientists. This was based on ORF's analysis of blanks. At one time, though, quality control analysis revealed a chrysotile contamination problem, so chrysotile analysis stopped for several weeks.

EPA extended the pilot plant study five weeks so more testing could be done. Information in scientific literature suggested chrysotile asbestos, unlike most other particles, was positively charged in the pH range of natural waters and of the filtration processes being used. Alum and polymer combinations that included anionic polymer were tried in the pilot plant research in order to test coagulation systems having both negative and positive charges. Logsdon and Symons analyzed the data from the filtration experiments and stated that three-stage rapid mixing for addition of alum and two polymers seemed promising.[5] Black & Veatch designed the plant so anionic polymer could be used in the treatment process.

Laboratory analyses of Duluth Water performed by the Lake Superior Basin Studies Group at the University of Minnesota at Duluth and by EPA in Duluth since the pilot plant study ended have repeatedly shown amphibole fibers but not chrysotile. Now we can conclude that Cook was right, Logsdon was wrong, and some problem existed with the ORF data.

Because EM analysis of water samples showed no chrysotile in raw or filtered water, Duluth filtration plant personnel decided to study discontinuing the anionic polymer feed. The chemicals fed at start-up were sodium hydroxide for pH adjustment, alum, nonionic polymer, and anionic polymer. Anionic polymer was specifically intended for chrysotile removal, so in the absence of chrysotile it might not be needed.

Preconditioning with alum and nonionic polymer only was studied first in the pilot plant. The anionic polymer injection was discontinued during three pilot plant runs. On all three occasions, the turbidity either decreased temporarily or remained the same. The results from electron microscope analysis of samples taken before and after anionic polymer discontinuation indicated no significant difference (0.064 million amphibole fibers per liter both with and without anionic polymer).

Next the anionic polymer feed was turned off in the main filter plant for 48 hours to allow the system to reach equilibrium. Before the anionic polymer feed was resumed, a sample of the effluent was taken. Five hours later, another effluent sample was taken. Electron microscope analysis revealed a much higher concentration of amphibole fibers in the sample taken during anionic polymer addition (0.51 million amphibole fibers per liter with anionic compared to 0.032 million fibers per liter without).

As a result of the pilot plant and full scale studies, anionic polymer is no longer used at the Duluth filtration plant. This results in some cost saving, because alum and nonionic polymer doses were not increased when anionic polymer use was discontinued.

Control of pH

In the pilot plant study, many variables were investigated, but very little was done to determine the effects of pH on treatment. In most cases pH was not adjusted during treatment.

After the plant was placed into operation, the effect of pH on asbestos removal was studied. The optimum pH for asbestos fiber removal was 7.05 to 7.15 for much of the year. During the summer of 1978 the raw water temperatures were higher than normal (55^{o} - 58^{o} F) because of predominant northeast and east winds. At this time the optimum reaction pH was lower than in the past and feeding caustic soda was unnecessary. During the summer of 1977, caustic was fed all summer because the reaction pH remained the same throughout raw water temperature changes.

In order to form floc with the same physical characteristics, a lower pH now seemed to be required. The cause of this was unknown. One possible cause was thought to be a change in the primary coagulant, alum. When alum from another supplier was used, however, the same problem developed.

During subsequent winter months, studies on full scale plant pH indicated definitely that alum purchased from Cloquet, Minnesota had a different pH-temperature relationship than alum purchased from other suppliers. Two curves for plant operational pH control were developed and are shown in Figures 6 and 7. These curves are used daily to guide operators to the optimum pH for asbestos removal when raw water temperature changes. See Apprendix E for Figures 6 and 7.

Fluoride

Data showed that a lower alum dose was required in the pilot plant than in the filter plant to produce the same effluent turbidity. Because no fluoride was injected into the pilot plant during those studies, plant personnel concluded that less alum could be used in the filter plant if the application point of the fluoride were moved, because fluoride in water can form a soluble complex with aluminum.[9]

The fluoride, which is maintained at 1 mg/L in the effluent, was discontinued, with prior approval from the Minnesota Department of Health, for a few days in January, 1978. This was an appropriate time to study the effect of fluoride addition since the raw water quality is very stable during the months of January and February because of ice cover on portions of Lake Superior. The results of this fluoride elimination study are listed in Table III. The results of samples for turbidity and amphibole fibers were slightly higher than usual when the coagulant dose was reduced to 8 mg/L of alum. At a dosage of 8 mg/L of alum the pH was slightly higher than the normal operating pH. Without other means of lowering pH the lower limit of the alum feed is probably 8 mg/L.

On January 30, an extra 4 mg/L of alum was required with the fluoride addition to produce the same turbidity that resulted from 10 mg/L of alum with no fluoride addition. Thirty percent of the alum added for flocculation could possibly be complexed with fluoride.

In the summer of 1978 the fluoride injection point was moved from the filter influent flume to the filter effluent flume. The optimum reaction pH during this time was lower than it had been previously. Because of this change in optimum pH, addition of sodium hydroxide was discontinued. The alum dose applied to the water to depress the pH was greater than the minimum required for particulate removal. Therefore, until feed equipment for the addition of acid or CO_2 for pH suppression is added to the plant, determining if the change in the fluoride application point has provided an operational advantage is not possible.

TABLE III

FLUORIDE ELIMINATION STUDY TEST RESULTS

DATE (1977)	FLUORIDE	ALUM mg/L	TURBIDITY NTU	SAMPLE NO	AMPHIBOLE CONCENTRATION 10^6 fibers/liter
1/18	Yes	12	.035	280	0.010
	None	12	.037	282	0.014
1/20	None	12	.038	283	BDL (0.011)
1/23	None	12	.038	284	0.005
1/24	None	10	.038	285	BDL (0.019)
	None	10	.035	286	0.014
1/25	None	8	.046	288	0.038
	None	8	.043	289	0.029
1/27	None	10	.038	290	0.019
	None	10	.038	291	0.010
1/30	None	10	.035	292	0.043
	None	10	.034	293	0.019
	Yes	14	.035	294	0.014
	Yes	14	.034	295	0.010

SUITABILITY OF MONITORING METHODS

Monitoring of filtered water quality by electron microscopy is necessary in order to determine the asbestos fiber content of treated water. Because EM analysis of water samples is both a time-consuming and a costly method, other monitoring techniques were investigated. The more promising methods are turbidimetry and particle counting. Comparisons are covered later in this section. A general overview is given below.

X-Ray Diffraction

X-ray diffraction cannot be used as a monitoring tool for the effluent water. Analysts cannot filter enough water to deposit a detectable mass of amphibole material on the filter because alum floc clogs the membrane filter. The time required to analyze a sample is quite lengthy (3-4 days). X-ray diffraction does not provide an answer fast enough for use at the filtration plant. Because the x-ray method generally yielded "Below Detectable Limit" (BDL) values for filtered water, x-ray diffraction tests were discontinued. The BDL values could not be correlated with other water quality parameters in efforts to relate water quality to easily monitored characteristics such as turbidity.

Turbidity

Turbidity can be used as an indication of changes in the effluent quality; however, no direct correlation between effluent turbidity and fiber concentration exists (see Fig. 2). Turbidity monitoring is useful even in the absence of a direct correlation between amphibole fibers and turbidity. Plant operators can use an increase in effluent turbidity as a signal that coagulant chemical dose should be increased or a filter should be backwashed.

Particle Counting

The HIAC particle counter has been very useful for monitoring the effluent quality and is now used as an in-line piece of equipment. The average particle count of the plant effluent is approximately 1 particle per mL, or 1000 particles per liter. The flow rate and the counting period are set to analyze 10 mL of water in an in-line mode. Particle counts in filtered water at Duluth are very low. The filter plant is very effectively removing particulates.

Methods of particle counting affect the results. Results obtained by connecting the particle sensor directly to a filter effluent tap are lower than results that were obtained when samples were collected and brought to the counter. This suggests that sample contamination by particles in treatment plant and laboratory air routinely occurs.

Optical Detector

Development of an optical detector that could differentiate between

fibers and clay particles on the basis of particle shape (rod vs. spheres) was pursued through a research grant from the Drinking Water Research Division to the Physics Department at the University of Minnesota Duluth.[12]

Turbidity and X-Ray Diffraction, Electron Beam Analysis and Comparison

Previous work[15] on Lake Superior water had indicated a positive correlation between x-ray analysis (amphibole mass) and electron beam analysis (amphibole fiber count). From January 18, 1977, through June 26, 1978, seventy-two samples were taken of the Duluth Filter Plant raw water influent for comparison analysis using x-ray diffraction and electron beam. These samples cover a wide range of weather conditions* and asbestiform concentrations. Within certain limitations, there is a correlation between the results of x-ray analysis and the results of electron beam analysis.

Data Analysis

The data are listed in Table 4 to show a comparison of each sample. There was no apparent difference in fiber sizing between the samples. There were significant differences from sample to sample in turbidity and suspended solids concentration. The ratio of amphibole mass (as determined by x-ray diffraction analysis) to suspended solids was determined to illustrate the percent of amphibole material present in each sample. This ratio was used because a stormy weather condition on Lake Superior caused a dramatic increase in the results from the electron microscope analysis without a similar increase in amphibole mass from the x-ray diffraction analysis.

A least squares regression analysis was used to compare x-ray diffraction results to electron microscope results in four different ways. Table 5 shows a tabulation of the results of the linear regression analysis.

The first analysis included all the data points listed in Table 4. The correlation between the two samples was poor. By eliminating the samples with amphibole mass to suspended solids (SS) ratios of less than 0.05 (5% of the sample suspended solids was amphibole mass), a positive correlation between the two samples was indicated (see Table 5, analysis 2). By examining Table 4, it can be seen that the samples with amphibole mass to suspended solids ratios of less than 0.05 are the higher turbidity samples.

The third and fourth analysis also showed improvements in the correlation factor as the percentage of amphibole material increased. This indicates that samples containing more clay and debris (like samples taken

* Stormy weather conditions will stir-up the bottom sediments by wave action.

during stormy weather conditions) produce abnormal x-ray analysis results. These abnormal results may be caused by absorption of the x-rays by the clay and debris and/or the covering of amphibole material by clay and debris.

The fifth analysis indicated a strong positive correlation between the turbidity and the suspended solids. A comparison of turbidity and x-ray diffraction analysis (analysis 6) yields no correlation between these two parameters. The same conclusion is true for a comparison of suspended solids and x-ray diffraction (analysis 8). The comparison of turbidity and electron microscope analysis for the raw water results indicates a strong positive correlation (analysis 7). Turbidity could be used as an indicator of fiber concentrations in the raw water influent for the filter plant; however, this correlation is not very good when the higher turbidity points (turbidities greater than 2 NTU) are excluded from the calculations (see analysis 9).

Daily monitoring of the raw water with x-ray analysis is not necessary. The concentration of amphibole material in the raw water has little effect on the filtration plant performance. Amphibole fibers are not removed effectively until the turbidity is effectively removed. Experience has shown that high amphibole fiber concentrations can be removed.

X-ray diffraction analysis does not provide results any faster than electron microscope analysis.

A minimum of three days is required for preparation and analysis of a sample taken for either method.

X-ray analysis does not yield an accurate measure of amphibole material during stormy conditions. The results obtained from x-ray analysis are considerably lower, as seen in Table 4.

TABLE 4

AMPHIBOLE MASS vs SUSPENDED SOLIDS

DATE	AMPHIBOLE (10^6 fibers/liter)	TOTAL	X-Ray AMPH MASS (mg/L)	TURB NTU	SUSPENDED SOLIDS (mg/L)	RATIO AMPH MASS TO SS
1-18-77	37	200	.07	.43	.66	.1061
1-18-77	41	160	.07	.43	.66	.1061
1-20-77	31	140	.03	.41	.45	.0667
1-21-77	40	210	.05	.52	.49	.1020
1-22-77	43	160	.04	.39	.40	.1000
1-23-77	44	140	.09	.54	.69	.1304
1-24-77	44	240	.05	.45	.48	.1042
1-25-77	35	200	.09	.36	.35	.2571
1-26-77	38	150	.16	.33	.35	.4571
1-27-77	19	140	.03	.30	.19	.1579
1-28-77	29	210	.04	.38	.11	.3636
1-29-77	35	180	.03	.37	---	
1-30-77	42	230	.04	.35	.41	.0976
2-01-77	29	120	.02	.25	.35	.0571
2-03-77	49	210	.05	.36	.38	.1316
2-05-77	41	140	.03	.28	.31	.0968
2-12-77	55	146	.04	.28	.28	.1429
2-18-77	20	120	.05	.36	.56	.0893
2-19-77	17	102	.06	.44	.64	.0938
3-21-77	38	96	.07	.41	.42	.1668
4-06-77	57	143	.10	.35		
6-14-77	134	250	.35	.62	.70	.5000
6-16-77	150	260	.19	.60	.69	.2317
6-22-77	168	271	.22	.67	1.07	.2056
7-13-77	145	192	.19	.56	.82	.2317
7-18-77	77	139	.04	.60	.73	.0548
7-18-77	130	180	.04	.60	.73	.0548
7-26-77	65	190	.09	.47	.57	.1579
8-01-77	51	190	.10	.45	.51	.1961
8-12-77	180	500	.40	1.7	2.5	.1600
8-16-77	81	300	.10	.84	1.02	.0980
8-24-77	75	310	.13	.82	.87	.1494
8-30-77	24	110	.03	.40	.74	.0405
9-06-77	77	120	.06	.68	.91	.0659
9-14-77	65	180	.12	.68	.77	.1558
9-28-77	69	200	.11	1.6	1.77	.0621
10-04-77	72	50	.09	2.6	2.49	.0361
10-08-77	830	1800	.29	11.0	10.6	.0274
10-12-77	120	270	.07	2.3	2.48	.0282
10-19-77	26	150	.05	.85	.80	.0202
10-26-77	18	89	.04	.60	.56	.0714
10-31-77	20	55	.03	.56	.62	.0484

TABLE 4 (Cont.)

DATE	AMPHIBOLE (10^6 fibers/liter)	TOTAL	X-RAY AMPH MASS (mg/L)	TURB NTU	SUSPENDED SOLIDS (mg/L)	RATIO AMPH MASS TO SS
11-07-77	5.6	34	.04	.51	.59	.0678
11-16-77	34	57	.04	.47	.52	.0769
11-22-77	6.6	41	.08	.62	.72	.1111
12-02-77	6.5	31	.04	.48	.54	.0737
12-07-77	90	170	.07	.83	.95	.0737
12-20-77	120	210	.37	1.4	1.97	.1878
1-04-78	60	100	.08	.46	.50	.1600
1-06-78	96	200	.17	.13	1.00	.1700
1-10-78	21	91	.07	.47	.54	.1296
1-18-78	24	80	.07	.42	.64	.1094
1-24-78	27	63	.08	.40	.44	.1818
2-07-78	75	160	.08	.86	.93	.0860
2-14-78	6.1	32	.06	.56	.59	.1017
2-24-78	44	126	.11	.57	.40	.2750
3-06-78	55	130	.07	.51	.53	.1321
3-16-78	48	100	.08	.48	.50	.1600
3-21-78	40	76	.05	.72	.77	.0649
3-28-78	36	74	.04	.68	.60	.0667
4-05-78	100	250	.36	.82	.82	.4390
4-11-78	250	490	.61	1.5	2.15	.2837
4-17-78	190	310	.55	.73	.82	.6707
4-25-78	210	320	.81	.89	1.23	.6585
5-01-78	200	370	.54	.94	1.06	.5094
5-08-78	160	310	.40	.62	.83	.4819
5-15-78	110	240	.36	.52	.64	.5625
5-23-78	160	280	.20	.50	.51	.3922
5-30-78	500	1800	.16	15.0	11.9	.0134
6-05-78	130	230	.13	1.0	1.02	.1275
6-12-78	170	360	.24	.80	1.20	.2000
6-26-78	99	220	.11	.81	.93	.1183

TABLE 5

LINEAR REGRESSION ANALYSIS OF X-RAY DIFFRACTION

AND ELECTRON MICROSCOPE RESULTS

ANALYSIS NO.	NO. OF POINTS	LIMITING AMPHIBOLE MASS SS	A	B	R^2	R
1	72	None	0.0801	0.0007	0.2455	0.4954
2	66	>.05	0.0294	0.0023	0.7047	0.8394
3	55	>.07	0.0260	0.0024	0.7374	0.8597
4	8	>.40	0.0222	0.0029	0.8050	0.8972
5	70	None	0.2102	0.8468	0.9781	0.9890
6	72	None	0.7480	1.0764	0.0219	0.1478
7	76	None	0.1775	0.0131	0.7749	0.8803
8	71	None	0.6895	1.9419	0.0471	0.2169
9	70	None	3.9422	1.0998	0.3519	0.5932

Equation $y = A + Bx$

x = amphibole (10^6 fibers/liter)

y = X-RAY amphibole mass (mg/l)

A = y intercept

B = slope

R^2 = coefficient of determination

R = correlation factor

Particle Counter and Electron Beam Analysis and Comparison

A particle counter (HIAC Instruments Division Model PC-320) was purchased in November 1977 to investigate the use of particle counting to monitor filter effluent quality and to attempt a correlation between particle counts and fiber counts obtained by electron microscopy. No attempts were made to correlate the raw water data because particle concentration in the raw water exceeds the counting capabilities of the particle counter sensor.

Data Analysis

The samples and results are listed in chronological order in data Table 6. The raw water quality and characteristics changed very little during the sampling period. Ice cover on Lake Superior over Duluth's intake structure allowed no wind action to re-suspend bottom sediments. Also, little or no surface run-off water, which contains a high concentration of clay, was introduced into Lake Superior because of the freezing temperatures.

The data were analyzed using the method of least squares by a curve fitting program on a Hewlett-Packard 29C. The program can be used to fit data to four types of curves: 1. Straight lines (linear regression); $y = a + bx$, 2. Exponential curves; $y = ae^{bx} (a>0)$, 3. Logarithmic curves; $y = a + b\ln x$, 4. Power curves; $y = ax^b (a>0)$. In this program, the regression coefficients a and b are found from solving the following equivalent of linear equations:

$$\begin{bmatrix} n & \Sigma X_i \\ \Sigma X_i & \Sigma X_i^2 \end{bmatrix} \begin{bmatrix} A \\ b \end{bmatrix} = \begin{bmatrix} \Sigma Y_i \\ \Sigma Y_i X_i \end{bmatrix}$$

The relations of the variables are defined as follows:

Regression Method	A	X_i	Y_i
Linear	a	x_i	y_i
Exponential	ln a	x_i	$\ln y_i$
Logarithmic	a	$\ln x_i$	y_i
Power	ln a	$\ln x_i$	$\ln y_i$

The coefficient of determination is:

$$r^2 = \frac{A\Sigma Y_i + b\Sigma X_i Y_i - \frac{1}{n}(\Sigma Y_i)^2}{\Sigma(Y_i^2) - \frac{1}{n}(\Sigma Y_i)^2}$$

The coefficient of determination is a mathematical expression relating the data to the calculated curve. When $r^2 = 1.0$, the data fits the calculated curve exactly. Values of r^2 below 1.0 represent a deviation from a perfect fit. The deviation increases as the r^2 value decreases from 1.0.

Thirty-four samples were analyzed using the above method. The coefficients are:

$$a = 4738.13$$

$$b = 18.77$$

$$r^2 = 0.26$$

$$n = 34$$

$$y = 4738.13 + 18.77x$$

where: x=particles per 100 mL and y=amphibole fibers per liter.

TABLE 6

PARTICLE COUNTS, TURBIDITY AND ELECTRON MICROSCOPE COMPARISON

Date	Particle Counter particles/100 mL	Turbidity NTU	Electron Microscope Amphibole Fibers per Liter	Total
1/18	1167	.033	9.6×10^3	1.8×10^5
1/18	649	.032	1.4×10^4	1.8×10^5
1/23	388	.038	4.8×10^3	6.2×10^4
1/24	410	.038	1.4×10^4	6.2×10^4
1/25	1137	.046	3.8×10^4	9.6×10^4
1/27	407	.038	1.9×10^4	1.3×10^5
1/27	436	.038	9.6×10^3	1.7×10^5
1/30	753	.034	4.3×10^4	6.7×10^4
1/30	622	.034	1.9×10^4	1.2×10^5
1/30	920	.035	1.4×10^4	1.4×10^5
1/30	670	.034	9.6×10^3	1.8×10^5
2/06	2800	.038	1.9×10^4	1.6×10^5
2/08	865	.036	1.9×10^4	2.2×10^5
2/10	590	.032	9.6×10^3	2.9×10^5
2/14	1495	.032	9.6×10^3	1.3×10^5
2/15	880	.031	(BDL 4.8×10^3)	7.8×10^4
2/27	1684	.032	3.8×10^4	1.7×10^5
2/27	1714	.032	9.6×10^3	3.7×10^5
2/27	1397	.033	4.8×10^4	3.6×10^5
2/27	1597	.035	1.9×10^4	4.3×10^5
2/27	3027	.034	(BDL 9.6×10^3)	2.1×10^5
2/27	2259	.036	2.9×10^4	2.1×10^5
2/27	2250	.033	4.8×10^4	2.9×10^5
2/27	1450	.033	9.6×10^3	1.9×10^5
3/06	3599	.037	4.8×10^4	3.5×10^5
3/06	2321	.039	5.8×10^4	4.9×10^5
3/06	2715	.039	1.2×10^5	7.3×10^5
3/06	3482	.039	1.3×10^5	7.3×10^5

TABLE 6

PARTICLE COUNTS, TURBIDITY AND ELECTRON MICROSCOPE COMPARISON

(Continued)

Date	Particle Counter particles/100 mL	Turbidity NTU	Electron Microscope Amphibole Fibers per Liter	Electron Microscope Total Liter
3/06	2312	.039	7.6×10^4	5.9×10^5
3/10	2268	.037	1.9×10^4	2.3×10^5
3/10	1731	.036	1.9×10^4	2.5×10^5
3/10	1681	.041	1.9×10^4	1.3×10^5
3/10	1404	.034	9.5×10^4	4.0×10^5
3/10	1409	.034	9.5×10^4	5.5×10^5

FILTER STRESS CONDITIONS

To be assured effective asbestiform fiber removal, the Duluth water filtration plant produces the highest quality water possible. Various "stresses" caused by normal operating procedures can affect the effluent quality of the filter plant. These "stress" conditions change the filtration rate during the filter run.

One of the first observations of filtration rate change effects was made by Baylis[10] in 1939-1940. He noted surging, or momentary fluctuations, of the levels of the mercury manometers installed in the flow-meters of some of the filters at the Chicago plant: "Slight surging is not objectionable, but when they (surges) are great, they cause the passage of coagulated matter through the filter."

In 1956, Hudson[11] reported, without supporting experimental evidence, that an unsteady flow severely upsets the operation of the filters and that filters operated under unsteady flow conditions cannot be expected to produce good water. He noted a plant with unsteady flow conditions with a visible grey haze around the submarine light in the filtered water reservoir.

In 1962, Cleasby[12] observed that large amounts of pre-deposited material was flushed through the filter and into the effluent by rate changes. He noted that greater rate changes seemed to have greater effects on the effluent quality. An increase in the duration of the rate disturbance did not significantly increase the total effect or the amount of material flushed out. In 1963, Cleasby[13] observed that more rapid filtration rate changes caused more material to be flushed through the filter than gradual filtration rate changes. The amount of material flushed through the filter was dependent on the type of material being filtered.

These observations were made before the use of polymers became common. Polymers are known to reduce the filter set-up or ripening time and increase filtration efficiency. They can also be used to "stabilize" filters, making the filters less susceptible to changes in the filtering rate, the chemical feeds, or the influent water quality. Some work has been accomplished since the advent of polymers.

In 1975, Kawamura[14] noted that shock loads created by taking one filter off line for backwashing could cause degradation of the filter effluent. He recommended that no less than four filters be designed into a treatment facility to alleviate some of the impact of the filtering rate change. He also noted that constant rate filtration can suffer filter effluent degradation by the hunting process of the flow controller to balance the flow among the filters. Development of negative pressure in the filter media towards the end of a filter run may also contribute to filter effluent degradation.

Scope

Three different "stress" conditions were researched during this study at two different plant capacities. The first "stress" was caused by stopping plant operations during a filter run and then starting plant operations again approximately six hours later. This is referred to as filter restart later in this paper. Since the filters had not reached the terminal headloss or suffered turbidity breakthrough, the filters were restarted at the end of this shut down period in a partially used condition. The filtration rate changed from 0 gpm/ft^2 to 3.25 gpm/ft^2 and from 0 gpm/ft^2 to 4.87 gpm/ft^2 at the higher plant rates in approximately 15 minutes.

The second "stress" was caused by removing one of the four filters for backwashing. The filtration rate of the three remaining filters was increased from 3.25 gpm/ft^2 to 4.33 gpm/ft^2 and from 4.87 gpm/ft^2 to 6.49 gpm/ft^2 within 60 seconds. There is a slight buffering of the increase because the water level over the filters increases.

The third "stress" was caused by placing a clean filter back into service. The filtering rate increased from 0 gpm/ft^2 to 3.25 gpm/ft^2 and from 0 gpm/ft^2 to 4.87 gpm/ft^2. There is no predeposited material to be "sloughed" off during this filtering rate increase. During the set-up time of approximately one hour, the effluent turbidity drops from its start-up high (less than 0.10 NTU) to the normal operating rate of less than 0.04 NTU.

General Information

The research goal was to run the tests under normal operating conditions and to study the effects of the filtration rate changes caused by the restart stress, backwash stress and the set-up stress.

Two types of filters exist in the treatment plant. Filter number one is a dual media filter with 21 inches of anthracite coal and 9 inches of silica sand. Filters number two, three and four are mixed media filters with 16.5 inches of anthracite coal, 9 inches of silica sand and 4.5 inches of garnet sand. These two types of filters were used in the research study for a comparison of removal efficiency, filtration stability and run duration. Filters number 1 and 2 were used most of the time because they were set up with sampling taps at various depths in the filter media. These filters are located geometrically so that detention time ahead of each filter should be identical and each filter should receive the same quality influent water.

Three treatment modes are available for use in the filtration plant which include two variations of direct filtration and conventional treatment. The flow patterns for the three modes are: 1) rapid mix to filtration, 2) rapid mix to flocculation to filtration and 3) rapid mix to flocculation to sedimentation to filtration. The mode labeled as direct in this paper refers to the rapid mix to filtration mode. Tests were performed in the two different treatment modes (1 and 3) to identify any differences that occur. These

differences are described in each stress condition section of this paper.

During the winter months, when the water temperature is at or below 39°F, little or no settling occurs in the sedimentation basin. The filter plant essentially operates in the direct filtration mode with a long detention time between the rapid mix and the filters.

The data for each stress condition were tabulated in a similar manner. For each run number, the following information was recorded: 1) the number of the stressed filter, 2) the approximate influent turbidity during the test, 3) the headloss of the filter during the test, 4) the chemical feed rates and 5) the treatment mode. The headloss is the key indicator for filter use time. A high headloss indicates a longer use time and a dirtier filter. A dirty filter has more material that can be sloughed off of the media during a stress condition. Dirty filters also have fewer available attachment sites and less area for water flow. The set-up stress analysis was performed on clean, freshly washed filters and was not affected by headloss. Each run on the set-up stress analysis exhibited headlosses consistent with the normal starting range of 2.0 - 2.5 feet.

The chemical feeds were adjusted for optimum removal of particulates during any time period. The alum coagulation process is very sensitive to pH changes. A pH of 7.1 over the top of the filters during these tests provided the optimum use of chemicals for the removal of particulates and asbestiform materials. Therefore, the dosage rate listed in the tables for the caustic soda feed is an average value. The caustic soda feed rate is changed periodically because of changes in the raw water.

More aluminum sulfate is required when the influent turbidity increases in order to maintain the removal efficiency. The increased aluminum sulfate is needed to remove the increased amounts of clay and other minerals present. A turbidity increase in the raw water source does not necessarily represent a corresponding increase in asbestiform particulates.

During the summer months, the plant is occasionally run at a 30 MGD rate to keep up with consumer demand; therefore, the tests were conducted at the 20 and 30 MGD filtration rates.

Filter Restart Stress - 20 MGD Plant Rate

The summary of data for the restart tests is tabulated in Table 7. The headloss value at the time of each test represents a time frame from which comparisons can be made between runs. The filters are normally backwashed at 8.0 feet of headloss. Two of the tests were performed on filters with 9.0 feet of headloss. The filter had not been backwashed before the plant was shut down because the backwash water storage basin was full. Upon start-up, the headloss gauges read 9.0 feet. These two tests provided excellent examples of the restart

"stress" on dirty filters.

The results of the 20 MGD restart tests are presented in Appendix A, in graphs 1 through 8. Generally, less than one-half hour was required for the filters to recover from the initial rate change and return to the normal removal efficiency. Test number 1 and the two tests on the filters with the 9 foot headloss, numbers 3 and 8*, exhibited turbidity and fiber breakthrough. The remaining tests revealed no significant changes in the fiber counts (electron microscope analysis) during the filtering rate change. Only slight turbidity breakthrough effects occur when the headloss upon restart is less than 7.5 feet.

The shut-down time ranged from 4.5 to 7.0 hours with an average of 5.9 hours. There appeared to be no adverse effect on the effluent quality of the filters that could be related to the duration of the shut-down period. During the shut-down period, the physical condition of the water in the filter area changed very little. The floc that forms settles out over the top of the filters during the shut-down period.

The dual media filter and the mixed media filters responded similarly to the filtering rate change. There is no significant difference in fiber counts (electron microscope analysis) in the effluents of the two types of filters.

There is no correlation between turbidity and fiber concentration. In fact, fiber concentration changes appeared to lag behind turbidity changed.

Filter Restart Stress - 30 MGD Plant Rate

The data summary for the 30 MGD restart stress tests is tabulated in Table 8. The 30 MGD tests were performed using the same criteria as the 20 MGD tests. Some changes were made in chemical feeds because of a change in process requirements. Sodium hydroxide was no longer required to meet pH limitations and anionic polymer use had been discontinued.

Graphs 9 through 16 in Appendix A show the effects of a filter restart at 30 MGD on turbidity and fiber release. No direct correlation can be drawn between turbidity and fiber concentrations. At times, graphs 10, 13, 15, fiber concentrations increased quite rapidly and the turbidity only increased slightly. Graphs 12 and 16 indicate the opposite, the fiber concentrations remained stable but the turbidity increased. Both support the idea that no direct correlation exists.

* Note: The scale on the y-axis for runs numbers 3 and 8 differs from the other six runs.

Breakthrough occurred during runs 10, 12, 13 and 15. These runs are all considered as low headloss runs and include both filters 1 and 2 and both treatment modes. The high headloss runs (9, 11, 14, 16) revealed no breakthrough or performance breakdown.

The two types of filters performed equally well. No difference can be seen between the two different media configurations. The treatment mode had no effect on effluent quality.

TABLE 7

Summary of Data - Filter Restart Stress - 20 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Down Time (hrs)	Treat-ment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
1	D	0.65	2.0	12.3	0.102**	7.1	6.0	Conv	0.055	0.380
2	M	0.60	2.0	12.3	0.081	7.1	7.0	Conv	0.070	0.038
3	M	0.70	9.0	12.3	0.080	7.1	4.5	Conv	0.122	2.2
4	D	1.8	2.5	17	0.10	7.1	5.5	Conv	0.054	* BDL
5	D	0.52	3.5	14	0.095	7.1	5.5	Dir	0.042	0.019
6	M	0.60	2.7	18	0.105	7.2	6.5	Dir	0.036	0.038
7	M	0.47	6.9	14	0.095	7.2	6.0	Dir	0.04	* BDL
8	D	0.47	9.0	14	0.095	7.2	6.0	Dir	0.710	2.1

*Detection Limit = 0.038 x 10^6f/L **also 0.065 mg/L anionic polymer

TABLE 8

Summary of Data - Filter Restart Stress - 30 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Down Time (hrs)	Treat-ment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
9	M		7.0	18.1	.074	6.7	5.5	Conv	0.045	0.019
10	M		3.6	16.1	.077	6.9	5.0	Conv	0.041	0.019
11	D		7.2	16	.077	6.8	4.5	Conv	0.040	* BDL
12	D		3.7	16	.077	6.9	3.5	Conv	0.069	* BDL
13	M		5.4	12	.082	7.0	8.0	Dir	0.051	0.6
14	M		7.6	12	.080	7.0	11.0	Dir	0.046	* BDL
15	D		5.6	12	.080	6.9	4.5	Dir	0.072	0.058
16	D		8.0	16	.092	6.9	6.5	Dir	0.061	* BDL

*Detection Limit = .019 x 10^6f/L

NOTE: On run number 8, the rate controller had been set on a lower rate than normal prior to shut down. This had not been recorded and when the plant resumed operation it was returned to normal rate which was much too high.

Backwash Stress - 20 MGD and 30 MGD Filter Rate

The data summary for the backwash tests is tabulated in Tables 9 and 10. The headloss is recorded as a measure of filter use as stated earlier. A rapid filtering rate change can have a greater impact on dirtier filters because more material is available to be flushed out.

The results of each individual run are displayed in graphs 17 through 34, Appendix B. The first ten (10) graphs show results while operating at a 20 MGD filtering rate (3.25 gpm/ft^2) and will be discussed first.

Under the direct filtration mode, four out of six runs exhibited breakthrough of fibers and/or turbidity. Runs 4 and 6 were the exceptions. There is no apparent reason why these two runs did not show the same results except for the fact that they were performed using the mixed media filter.

No breakthrough occurred while operating in the conventional treatment mode. There was no significant difference between the background parameters of the various backwash stress runs. It can be concluded that the conventional treatment mode of operation was less affected by the backwash stress at this filtering rate.

At the increased filtering rate of 30 MGD (4.87 gpm/ft^2), none of the runs exhibited any breakthrough. Many of the samples taken were at or below the detectible limits for electron microscopy and turbidity.

Filter Start-up Stress - 20 and 30 MGD Filter Rate

The data summary for the filter start-up runs is listed in Tables 11 and 12. All runs were performed on filters backwashed just prior to the test. It was assumed that each filter was as clean as any other filter used in a test run. The filters were backwashed as usual. Visual inspection of the backwash effluent is used as the indicator to cease backwashing.

Samples from the initial 3-5 minutes of filtering time after backwash appear to be of clean backwash water because the turbidity and fiber concentrations are quite low. Then at about 5 minutes the turbidity and fiber concentrations increase and the run exhibits a normal set-up curve from that point on.

Tests using the 20 MGD filtering rate revealed no significant difference between the conventional and direct filtration modes; however, filter 1 appeared to take longer to set-up and samples taken contained much higher fiber concentrations.

Tests using the 30 MGD filtering rate revealed a difference between conventional treatment and direct filtration but no difference between dual and mixed media filters.

The results of each individual start-up stress run are shown on graphs 35 through 42 in Appendix C.

TABLE 9

Summary of Data - Backwash Stress - 20 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Treatment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
1	D	0.60	2.0	10	0.07*	7.3	Dir	.099	0.386
2	M	0.50	2.1	10	0.07*	7.3	Dir	.113	0.288
3	D	0.40	2.0	15	0.095**	7.2	Dir	.042	0.192
4	M	0.40	2.3	15	0.095**	7.2	Dir	.057	0.096
5	D	1.8	7.2	12	0.085***	7.2	Dir	.535	12.8
6	M	0.60	6.7	12	0.085***	7.2	Dir	.041	0.096
7	D	1.3	7.5	15	0.125	7.2	Conv	.075	0.038
8	D	1.8	2.0	18	0.13	7.3	Conv	.045	0.270
9	M	1.2	4.5	20	0.13	7.2	Conv	.036	0.038
10	M	0.40	2.8	14	0.07	7.2	Conv	.036	0.029

*also 0.06 ppm anionic polymer **also 0.075 anionic ***also 0.065 anionic

TABLE 10

Summary of Data - Backwash Stress - 30 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Treatment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
11	M	0.60	6.5	16	0.077	6.9	Conv	.039	.019
12	M	0.63	4.0	16	0.077	6.9	Conv	.038	.077
13	D	0.70	4.0	16	0.077	6.9	Conv	.11	*BDL
14	D	0.55	7.2	16	0.077	6.9	Conv	.144	.170
15	M	0.45	6.5	12	0.105	7.0	Dir	.040	*BDL
16	M	0.47	3.9	12	0.08	7.0	Dir	.047	.021
17	D	0.50	6.8	12	0.08	7.0	Dir	.040	*BDL
18	D	0.61	3.0	16	0.092	6.9	Dir	.050	*BDL

*Detection Limit = .019 x 10^6 f/L

TABLE 11

Summary of Data - Set-up Stress - 20 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Treatment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
1	D	1.4	2.0	12	0.085*	7.2	Dir	0.10	2.3
2	M	0.6	2.0	18	0.105	7.2	Dir	0.055	0.077
3	D	0.5	2.5	14	0.07	7.1	Conv	0.039	0.12
4	M	0.5	2.4	14	0.07	7.1	Conv	0.041	0.019

* also 0.065 ppm anionic polymer

TABLE 12

Summary of Data - Set-up Stress - 30 MGD

Run	Media	Infl Turb (NTU)	H_L (ft)	Alum (ppm)	Non-ionic (ppm)	pH	Treatment Mode	Maximum Filtered Water Turb. (NTU)	Amph. (10^6f/L)
5	M		3.5	18	0.079	6.8	Conv	0.043	0.019
6	D		3.5	16	0.077	6.9	Conv	0.055	0.077
9	D		3.5	14	0.098	7.2	Dir	0.067	0.82
10	M		3.5	14	0.098	7.2	Dir	0.072	1.5

*Note: Runs 7 and 8 were deleted because of phosphate interference with the alum due to the backwash water supply.

PILOT PLANT RESEARCH

When the filtration plant was built a pilot plant was purchased and installed in a room designed for pilot plant research. The pilot plant is a 10 gpm Neptune-Microfloc package plant with three-stage rapid mix. The pilot plant can be used to perform treatment studies to select effective chemical doses when raw water quality changes or to study treatment technique modifications when research cannot be done in the filtration plant. Some pilot plant studies have been done already and these are discussed in the paragraphs that follow.

Clay Injection Study

A clay slurry was prepared from the clay available behind the filtration plant to provide an artificial increase in turbidity and suspended solids in the influent. The influent turbidity could only be maintained between 4 and 10 NTU because the clay would not remain in suspension in the batch tank. The effluent turbidity remained between 0.040 and 0.050 NTU during the injection period.

During the second group of high suspended solids tests the influent turbidity was held at 10.0 NTUs. Six runs were made in two groups of three. All three runs in a group were performed on the same day in the winter, which provided a stable raw water influent. The alum concentration was set at 15, 20, 25 mg/L Consistent effluent turbidities were obtained between 0.035 and 0.04. The results are listed in Table 13. Although there was no significant difference in effluent turbidity, there was a decrease in fiber counts with the increased alum except in run 6, which was higher than run 5 but less than run 4. The graphic output of effluent turbidity was nearly duplicated for each run.

This indicated that the fibers are among the last particles to be removed by the alum coagulation process.

TABLE 13

HIGH SUSPENDED SOLIDS TEST RESULTS

Run	Alum Dose (mg/L)	Amph Fibers (10^6f/L)	Turbidity
1	15	0.067	.034
2	20	0.029	.032
3	25	0.0096	.031
4	15	0.12	.034
5	20	0.058	.032
6	25	0.11	.031

Alum Dose

Pilot plant tests show that at dosage rates less than 10 mg/L alum will not remove particulates as efficiently in the pilot plant as

in the full scale plant. Turbidity levels at the lower alum dosage rates were consistently 0.05 to 0.08 NTU or greater, as contrasted to 0.04 NTU water produced in the main plant. In the pilot plant dosage rates of greater than 10 ppm produce effluent water at 0.040 NTU or less. The alum dosage rate range is between 10 and 15 mg/L under normal operating conditions for the pilot plant.

Air Binding in Filters

Significant air binding problems occur in the pilot plant filter bed when the incoming water is 45°F or warmer. The headloss through the filter increases at a normal rate up to about three feet of headloss. From three feet to eight feet the headloss increases rapidly because of the air build-up. The air binding decreases the filter run length. The air binding problem on the pilot plant may be caused by two factors. One is a 2°F change of the water temperature through the filter. The other is the negative head produced by the effluent pump. Because the pilot plant has about two feet of water over the filter media and filter effluent is pumped, negative head conditions (pressure less than one atmosphere within the filter media) are likely to develop. This was also a problem in pilot plant research at Seattle as well as at Duluth in 1974. Air binding is not a problem in the main plant because the top of the filter box is 9 feet - 8 inches above the top of the filter media, so nearly seven feet of water can be maintained over the top of the media during filtration.

Optimum pH Study

An investigation was made using the pilot plant to establish an optimum pH operating range. Initially a filter run was set up to change the pH of the coagulated water every two hours and observe the change in turbidity. The results were misleading, however, because as the pH was being changed the condition in the filter bed, and hence the effluent turbidity, tended to reflect the effects of the previously applied pH. No noticeable change occurred in the first three pilot plant runs. At the same time the lower pH formed a different type of alum floc and drastically reduced the filter run length. Runs 4, 5, and 6 show a dramatic breakthrough at the end of the run with the lower pH. The run length of each of these runs was between ten (10) and fourteen (14) hours. The head loss (H_L) was around five (5) feet, except for number four (4) which was 8.4 feet.

The basic difference between each run was the amount of alum being fed into the influent. Alum was being used to lower or adjust the pH. The higher the alum feed, the higher the particle counts and breakthrough. The breakthrough occurred because of poorly coagulated alum at the low pH. Soluble forms of aluminum hydroxide were being formed.

The revised pH study revealed surprising results. The following pH values were used:

(1) 7.45
(2) 7.30
(3) 7.15
(4) 7.00
(5) 6.85

Each one was held constant through an entire filter run. Breakthrough occurred on each run except one (1) and two (2) above. A preliminary review indicates 7.30 to be slightly better than 7.45 because the particle counts are lower at the end of the run; however, there is not a significant difference between the two runs. (The difference between four (4) particles/mL and ten (10) particles/mL is very slight.)

Each run produced the same quality effluent before breakthrough, but the higher pH values produced longer filter runs:

7.45 - 18 hours
7.30 - 19 hours
7.15 - 18 hours
7.00 - 12 hours
6.85 - 12 hours

It must be taken into account that these runs were all performed in the winter with a colder, more consistent influent than can be obtained during the summer.

TABLE 14

Results of Revised pH Study

Run	Lengths (hrs)	pH	Alum (ppm)	Nonionic Polymer (ppm)	Chlorine (ppm)	Particle Count per mL	H_L at end of run (ft)
1	18	7.45	10	0.12	1.2	>10	8.2
2	19	7.30	10	0.12	1.2	4.3	8.0
3	18	7.15	10	0.12	1.2	27	7.1
4	12	7.00	10	0.12	1.2	13.5	4.2
5	12	6.85	10	0.12	1.2	23	3.4

Chemicals were fed at the following points: Alum, RM #2; Polymer, RM #3; Chlorine, RM #1; Sodium Hydroxide, RM #1; Sulphuric Acid, RM #1.

Pilot Plant Rapid Mix Study

During the pilot plant rapid mix study, the chemical feeds were held as constant as possible within the constraints of the influent water. Chlorine was always fed into rapid mix 1, alum into rapid mix 2 and nonionic polymer (985N) into rapid mix 3. By this sequence, any pH change caused by the chlorine took place before the alum was added. The polymer was added last to provide some bonding strength for the aluminum hydroxide floc.

The feed rates were as follows:

(1)	Alum	12 ppm
(2)	Nonionic Polymer	0.08 to 0.12 ppm
(3)	Cl_2	1.2 ppm

All three rapid mixers were held at the same operating rpm throughout each run. Corresponding velocity gradients (sec^{-1}) and rpm settings are listed in Table 15.

TABLE 15

G (sec^{-1})	Rpm
300	600
500	700
700	800

The power input was determined by reading power draw with an empty rapid mix chamber and subtracting this value from the power draw obtained with a full rapid mix chamber. The value of G can be obtained from the formula,

$$G = \frac{\Delta P}{(Vol \times \mu)}$$

where:

P = Power input

Vol = Vol. of chamber

μ = Kinematic viscosity

Twenty-five (25) runs were performed in the rapid mix study and were divided as follows:

(1) 800 rpm - 12.1 $\pm$ 2.3 hours
(2) 700 rpm - 13.7 $\pm$ 1.9 hours
(3) 600 rpm - 13.0 $\pm$ 2.1 hours

Each run length is shown in Table 16.

The runs performed using a mixing speed of 700 rpm were longer and had a smaller standard deviation. This compares favorably with the literature on G values which recommends a G value of 500 sec^{-1} for rapid mixing.

TABLE 16

Rapid Mix Study Results

	Run #	Approximate Length	
800 RPM	3	14	
	4	16	
	9	12	
	10	11	$\bar{x} = 12.1 \pm 2.3$
	11	9	
	12	11	n = 10
	18	10	
	23	14	
	24	10	
	25	14	
700 RPM	2	10.5	
	5	14	
	8	10	
	14	14	$\bar{x} = 13.7 \pm 1.9$
	15	16	
	20	14	n = 9
	17	15	
	21	14	
	22	15	
600 RPM	1	11	
	6	15	
	7	11	$\bar{x} = 13.0 \pm 2.1$
	13	13	
	16	16	n = 6
	19	12	

POST-CHLORINATION BACTERIA STUDY

Methods and Materials

This project was an effort to determine how effective the granular media filters are in removing bacteria. Pre-chlorination was discontinued for a period of three weeks and the plant was operated in the direct filtration mode while chlorine was added to the filter effluent channel downstream from the bacteria sampling points.

Bacteria counts were made on raw water, filter influent water to which the flocculation chemicals (alum and non-ionic polymer) had been applied, and the filter effluent water. Temperature, pH, effluent turbidity and chlorine residual were monitored also.

Results

The results of this study are outlined in Figures 4 and 5. Although the study was conducted for three weeks, only one week is shown in the figures because the other data had to be discarded. For the first two weeks, HVAC cooling water was being recirculated to the plant's rapid mix chambers. This cooling water contained enough chlorine so that weekly positive chlorine tests were sometimes observed in the filtered water samples. After turning off this cooling water, no positive chlorine tests were observed.

Operating in post-chlorination direct filtration mode resulted in effluent turbidities no lower than 0.04 NTU. Operating in prechlorination direct filtration mode can result in turbidities as low as 0.03.

Coliform bacteria were successfully removed in all cases except on August 16 when one appeared in 1,800 mL of effluent from filter number one. Number one is the dual media filter; the others are multi-media filters.

Coliform counts should be similar in the raw water and the filter influent water, but the raw water counts were higher. This was probably due to viable cells becoming trapped in the floc and not producing colonies by the MF method (the filter influent water contained the added floc-producing chemicals). The possibility that the cells became non-viable upon addition of the floc-producing chemicals seems remote since MPN determinations comparing raw and filter influent water were similar.

Heterotrophic bacteria counts were determined at $20^{o}C$, 72 hours and also at $35^{o}C$, 72 hours. Counts were higher, often considerably so, at $20^{o}C$ than at $35^{o}C$; however, confluence often interfered with accurate counts and spreaders often developed.

Heterotrophic bacteria counts were higher in the filter influent water than in the raw water. This was probably due to the polymer solution feed which often contains a considerable bacterial population.

Two samples on August 17 were also run for conventional SPC using Plate Count Agar (Difco). Agreement with the M-SPC was not particularly good as is indicated on Figures 4 and 5.

POST CHLORINATION BACTERIA PROJECT DATA

DATE	FILTER INFLUENT WATER pH	WATER TEMP., °F.	CHLORINE mg/L	RAW WATER				FILTER INFLUENT WATER			
				M-SPC* mL		COLI 100 mL		M-SPC* mL		COLI 100 mL	
				20°C	35°C	Sheen Clns**	Other Clns**	20°C	35°C	Sheen Clns**	Other Clns**
8/13	7.02	42	0	28	8	9	18				
8/14	7.22	41	0	SPR. (EST. 33)	SPR.	6	23	SPR. (EST. 80)	SPR. (EST. 33)	0	1
8/15	7.20	42	0	30	7	13 (MPN 4)	32	SPR. (EST. 90)	18	1 (MPN 5)	2
8/16	7.11	42	0	CONF. EST. 25	6	5	22	35	SPR. (EST. 15)	0	2
8/17	7.10	43	0	14 (SPC 31)	SPR. (SPC 3)	3 (MPN 4)	18	53 (SPC 81)	SPR. EST. 10 SPC8	0 (MPN 5)	0

SPR = Spreader
CONF = Confluence

* Membrane filter Std. Plt. Ct. agar for heterotrophic bacteria (13)

** Colonies

FIGURE NO. 4

POST CHLORINATION BACTERIA PROJECT DATA

INFLUENT WATERS

POST CHLORINATION BACTERIA PROJECT DATA

DATE 1979	FILTER INFLUENT WATER pH	WATER TEMP., °F.	TURBIDITY, NTU	FILTER NO. 1 EFFLUENT WATER				FILTER NO. 2 EFFLUENT WATER				
				M-SPC* 100 mL		COLI 1000 mL		TURBIDITY	M-SPC* 100 mL		COLI 1000 mL	
				20°C	35°C				20°C	35°C	SHEEN CLNS**	OTHER CLNS**
8/13	7.02	42	0.046	240	18	0	3	0.040	190	10	0	3
8/14	7.22	41	0.044	250	75	0	3	Filter No. 3 0.042	SPR	66	0	2
8/15	7.20	42	0.062	SPR (EST 400)	SPR.	0/ 1800	32/ 1800	0.052	SPR (EST 400)	32	0/ 1800	10/ 1800
8/16	7.11	42	0.063	CONF EST. 300	13	1/ 1800	21/ 1800	0.068	SPR. CONF. EST. 400	22	0/ 1800	29/ 1800
8/17	7.10	43	Filter No. 3 0.085	SPR. EST. 300	12	0/ 1800	3/ 1800	Filter No. 4 0.045	SPR. EST. 200	9	0/ 1800	7/ 1800

SPR = Spreader
CONF = Confluence

* Membrane filter Std. Plt. Ct. agar for heterotrophic bacteria (13)

** Colonies

All samples had zero chlorine residual

FIGURE NO. 5

POST CHLORINATION BACTERIA PROJECT DATA

EFFLUENT WATERS

SLUDGE HANDLING AND DISPOSAL

Introduction

The design of the Duluth Water Treatment facility included three lagoons for sludge thickening and storage. It had been thought that static freezing during one winter cycle would be adequate to thicken the sludge enough for hauling to a landfill in the summer months. The first winter operation indicated that this probably would have been satisfactory. However, the Minnesota Pollution Control Agency's stringent requirements dealing with the ultimate disposal of asbestiform fiber laden sludge made it necessary to develop lagoon operating procedures that would maximize sludge volume reduction. A research project was planned to accomplish this goal.

Parameters Studied

Pertinent parameters to be studied were considered to be weather, snow cover on lagoons, sludge volume pumped to lagoons, solids concentration of sludge, and thickness of ice cover in the lagoons. Two types of freezing were studied. Static freezing, when no attempt was made to pump sludge from under the ice cover to the surface; and layer freezing when sludge was either sprayed on existing ice or was pumped from under the ice to the surface to expose it to ambient temperatures in layers that would freeze overnight.

Physical Features and Equipment

Each of the three sludge lagoons at the Duluth facility is 342 feet long and 90 feet wide and has a depth of 8 feet to the overflow in the discharge structure. The discharge structures that return decant water to the wash water recovery building are equipped with 3" x 8" planks so that lagoons can be decanted to any desired level. Each of the three lagoons has an available storage volume of 3.5 acre feet. There are two four inch yard hydrants located at each lagoon for spraying the sludge. Sludge is pumped to the lagoons by a Model VPM 5656 Chicago pump which is located in the wash water recovery building. The pump is capable of pumping 170 gallons per minute at a total dynamic head of 150 feet.

A Sierra Misco Model # 1045 weather station was installed on the chemical and filter building to monitor weather.

Gas powered centrifugal pumps proved unsuccessful for recirculating the sludge so a diaphragm pump, Homelite Model 111DP3, was purchased and successfully used. Fire hose was used for both suction and discharge on the diaphragm pump but was abandoned in favor of PVC pipe after the first winter.

A snowmobile was used to transport gasoline, pumps, tools, etc. to and from the filter building garage and the lagoons.

Temperature measurements in the sludge were taken using a Cole Parmer Model 8502-25 centigrade thermometer utilizing Yellow Springs Instrument 700 series probes.

An ice fishing tent was used as a work shed at the lagoons so the workmen could do some of their work protected from weather and with some heat.

A gas powered auger, Ardisam Iskim Model 2000, was used to drill holes in the ice on the lagoons.

Methods

Snow cover on lagoon ice was measured, manually after each snowfall. The length of time between snowfall and snow removal from the lagoons was also recorded.

Holes were ice augered in each lagoon at three locations and the ice thickness was measured at each hole. The three measurements were averaged and the average was recorded.

During the winter of 1978-79, 2-1/2" fire hose was used for both suction and discharge on the diaphragm pump. After the experience of one winter with this method, some changes were made.

The problem encountered with the fire hose was one of vacuum collapse on the suction side and difficulty in moving the discharge end. Three inch (3") Schedule 80 PVC pipe was used for the suction and discharge sides of the diaphragm pump and worked much better. Pipe sections on the discharge side were connected with three foot (3') lengths of wire wound rubber hose for ease of manipulation. Three inch (3") brass evertight quick connect couplings were utilized for the rubber hose to PVC connections.

A method was needed for comparison of ice production between layer freezing and static freezing so a "freeze degree day" was used. A freeze degree day as used in this project is defined as the average daily temperature subtracted from 32°F. Freeze degree days for the winter season studied are tabulated in Appendix D.

Sludge volume pumped to the lagoons was determined by pumping sludge from the clarifier only when there was no incoming washwater to the clarifier. Then drawdown in the clarifier was measured manually and equated to volume pumped. The volume pumped to the lagoons was not utilized in analysis however because the lagoons are decanted prior to the winter season and initial solids content proved to be too variable to be used. It was planned to determine the volume of settled sludge by cross sectioning the sludge-water interface from a boat in the lagoon just before the freezing weather cycle. Then after the winter operation, it was thought that another series of cross sections would allow the sludge

volume reduction to be calculated. The volume reduction was so complete however that nothing remained that would lend itself to cross section survey. A thin layer (perhaps 1" thick) of solids that had a consistency similar to instant coffee was all that remained.

Using the techniques developed from this research, the Duluth Water and Gas Department has still not had to clean a lagoon after 5 years of operation because the sludge volume reduction is so complete.

Temperature profiles were taken in Lagoon #3 on December 21, 1979, and on January 21, 1980. These profiles are indicated below; all temperatures are in degrees fahrenheit.

	51"	Top of ice	51"	Top of ice
	38.5"	ice		
	36"	34.0°	31"	ice
	24"	40.7°	24"	38.3°
	12"	43.8°	12"	41.2°
Lagoon bottom	0	46.2°	0	43.8°
	Lagoon #3	12/21/79	Lagoon #3	1/21/80

The bottoms of these lagoons are well below the normal frost depth for December and January in Duluth.

Static freezing could be enhanced considerably if the heat at the lower elevations in the sludge could be dissipated.

Operational Considerations

This project started with the winter of 1978-79. Prior to that time, attempts were still being made to dispose of the thickened sludge as a normal solid waste. During this, the first winter, the importance of snow removal was not fully understood and snow was not removed quickly enough.

At the start of the freezing season, a hazard can exist because of thin ice covered with early snow. It was decided that a minimum of four inches (4") of ice was necessary to safely support the personnel and snow blower.

The average snow removal time per lagoon is three (3) hours. This can extend to several days after a heavy blizzard. Snow must be blown well away from lagoon edges or poor edge freezing results from snow insulation and ground temperatures. An Ariens eight (8) horsepower snow blower was used on this project and it did not throw snow far enough to

the side. Consequently, it was necessary to move the same snow three or four times during each removal process.

Even distribution of the sludge pumped from the clarifier was difficult to maintain. When attempts were made to use the lagoon inlet structures for sludge loading, the "warm" sludge tended to undermine the frozen ice layer at the lagoon edge near the inlet structure. It was necessary to spray the sludge from the hydrants and rotate the spray nozzles frequently. Even distribution leads to a smoother surface for more effective snow removal.

The lagoons at the Duluth Treatment Plant were constructed with 3.5 foot elevation difference between #3 and #2 and another 3.5 foot elevation difference between #2 and #1. This elevation difference between each lagoon is an advantage when transferring sludge to the downhill lagoon in the winter. It is a problem, however, in the spring when decanting water from the two upper lagoons with the present valving. Return water can only be shut off at the clarifier so the decant can back up into Lagoon #1 (the lowest) by way of the decant structure. If a valve were installed in the return piping at the tee for each of the lagoon pick up branch lines, this problem would not exist.

There were difficulties encountered in pumping sludge from under the ice for layer freezing. The Model 111DP3 Homelite diaphragm pump is small enough for one man to move but difficult during the set-up and take-down periods. Also it is of a size that it takes 24 hours of pumping time to build up a 6"-9" layer of sludge for layer freezing. Three (3) to three and one-half (3-1/2) per cent solids appears to be a limit for pumping with this pump under the prevailing conditions. That means that sludge that has been in the lagoon for one or more years requires thinning with water to reduce solids content so that it can be recircualted to a freezing environment. This proved to be a very labor intensive procedure.

Piping to and from the diaphragm pump should be chosen to give the least possible friction loss. Piping connections should be pressure fit, i.e. quick coupling because threaded connections are subject to sludge freezing in the threads. Anti-freeze liquids in the threads does help but quick couplings work even better.

All pumping required constant monitoring because if the pump quit, the entire system froze and had to be dismantled and thawed. Two people spend one to two hours each time a dismantle is necessary.

Better spraying characteristics could be obtained if there had been three hydrants matched in position to the inlet structures. Three hydrants would allow more even distribution of sprayed sludge.

Ice Production - Freeze Degree Days

Analysis of the data for ice production and freeze degree days indicated some interesting relationships. During the winter of 1978-79

on Lagoon #3 under static freezing conditions, 98 freeze degree days were required for each inch of ice development. The ice of Lagoon #3 was snow covered 50 percent of the time during the 1978-79 winter. During the same period, Lagoon #2 was snow covered 66 percent of the time and 117 freeze degree days were required for each inch of ice development under static freezing conditions. During the same 1978-79 winter, sludge was sprayed on Lagoon #1 to layer freeze and only 35 freeze degree days were required per inch of ice development.

During the winter 1979-80 static freezing prior to February 14 accomplished 32" of ice development at a rate of 38 freeze degree days per inch. Static freezing with good snow removal will yield ice at a reasonable rate until the ice cover reaches approximately 25". Then the rate declines drastically.

During the winter 1980-81 with layer freezing and good efforts at snow removal, the following ice development rates were reached:

Lagoon #1 - 31 freeze degree days per inch

Lagoon #2 - 28 freeze degree days per inch

Lagoon #3 - 34 freeze degree days per inch

Cost Consideration

Since the threat existed that the three available lagoons might be full of sludge before an acceptable final disposal arrangement could be reached, the usual economic considerations for comparison of efficiency in lagoon operation had to be set aside. Of first concern was keeping the filtration plant operational by not running out of storage capacity for backwash water sludge. Optimizing operational procedures for cost effectiveness had to be left for future research.

CORROSION CONTROL

Rusty Water Complaints

Very soon after the filtration plant was chemically operational (January 1977), the department was deluged with complaints of rusty water at the tap. Subsequent investigation indicated that the problems existed only in homes with galvanized iron or steel plumbing. It was thought that after a few weeks the distribution system would reach a new equilibrium with the filtered water so that the problem would solve itself. This did not happen so in June of 1977 research was started to determine the best corrective action.

Nature of the Problem

There are two basic areas of active corrosion in water distribution

systems; corrosion in transmission and distribution lines, and corrosion within the customers branch service. Chemical adjustment techniques generally employed are much more effective in the mains than in customers piping because water flow is, for the most part, continuous in a main and intermittent in a customer service line. Continual flow retards oxygen build-up on pipe surfaces and provides a good supply of inhibitor to the pipe surface; intermittent flow does not. Complaints in Duluth indicated that most of the corrosion occurs within galvanized steel pipes and is probably due mostly to the dissolved oxygen that saturates our water supply. This oxygen is released as the water sits in indoor pipes, or is heated by a water heater, and is concentrated on the pipe surface. As a result of these effects the corrosion within Duluth's water supply exists primarily in indoor galvanized steel plumbing and causes gradual pipe decay and brown water due to ferric iron in suspension.

Treatment Techniques

The first alternate investigated was adjustment by carbonate film theory. It was readily apparent that this method was not feasible due to economics. It would require a lime feed of 15 ppm and soda ash at 107 ppm to obtain a depository film with Duluth's water supply.

Zinc orthophosphate was investigated and on December 30, 1977, a liquid zinc orthophosphate (Virchem 932) was fed into the high service pump discharge line. Initially the zinc orthophosphate was fed at a rate of 3 ppm zinc. As the system indicated residual zinc throughout, the feed was tapered off to 0.15 ppm zinc on January 13, 1978. It is now fed at a rate of 0.13 ppm which seems to be adequate.

The zinc orthophosphate virtually eliminated corrosion within the distribution mains, but had only limited effect in indoor plumbing because of the previously mentioned poor reaction conditions that exist in indoor plumbing.

A research project was undertaken to find an additional technique for treatment of indoor plumbing. Duluth's distribution system consists of seven separate pressure levels. One of these is called the upper Lakeside system and it was selected for this research for three reasons.

a. The upper Lakeside system is an isolated system and all water used there is pumped through the Lakeside pump station.

b. The upper Lakeside system has rapid fill-empty cycles, so results of different possible chemical combinations were readily available.

c. The upper Lakeside system being relatively small allowed us to use a small, simple, temporary chemical feed system and mix chemical solutions by hand since the quantities needed were small.

These studies in the upper Lakeside system indicated that the most effective and most economical method of controlling corrosion and the corrosion products was to feed both an inhibitor (zinc orthophosphate) and a sequestering agent (sodium hexametaphosphate). The sequestering agent competes with the oxygen for the iron preventing the formation of ferric iron (rust).

The results of these studies are summarized in Table 17.

TABLE 17

Results of 8 Weeks of Corrosion Control

Tests in Upper Lakeside System

Before Hexametaphosphate Addition

Location	Tap	Total Iron (ppm)	Filterable Iron (ppm)	% Sequestered Corrected for Backgrd.	Total Phosphate (ppm)	Meta-Phosphate (ppm)	Ortho-Phosphate (ppm)	*Ferric Iron (ppm)
Jay St. Toolhse.	Hot	.33	0	0	.20	0	.20	.33
	Cold	.66	0	0	.20	0	.20	.66
Rockridge	Hot	.11	0	0	.23	0	.23	.11
	Cold	.12	.01	0	.30	0	.30	.11
Karo Residence	Hot	.28	0	0	.20	0	.20	.28
	Cold	.09	0	0	.31	0	.31	.09
Davidson Residence	Hot	.33	0	0	.19	0	.19	.33
	Cold	.22	0	0	.22	0	.22	.22

After Addition of Approximately 1 ppm Sodium Hexametaphosphate

Jay St. Toolhse.	Hot	.33	.05	7	.40	.05	.35	.28
	Cold	.66	.60	90	.97	.67	.30	.06
Rockridge	Hot	.11	.08	50	.90	.15	.75	.03
	Cold	.12	.11	83	1.3	.90	.38	.01
Karo Residence	Hot	.28	.10	22	.90	.28	.62	.18
	Cold	.09	.09	100	1.4	1.0	.38	.00
Davidson Residence	Hot	.33	.04	3	.80	.25	.55	.29
	Cold	.22	.20	89	1.2	.85	.35	.02

* Ferric iron is visible when it exceeds 0.2 ppm.

SECTION VI

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SECTION VII

APPENDICES

A. FILTER RESTART STRESS

B. BACKWASH STRESS

C. CLEAN FILTER START-UP STRESS

D. FREEZE DEGREE DAYS

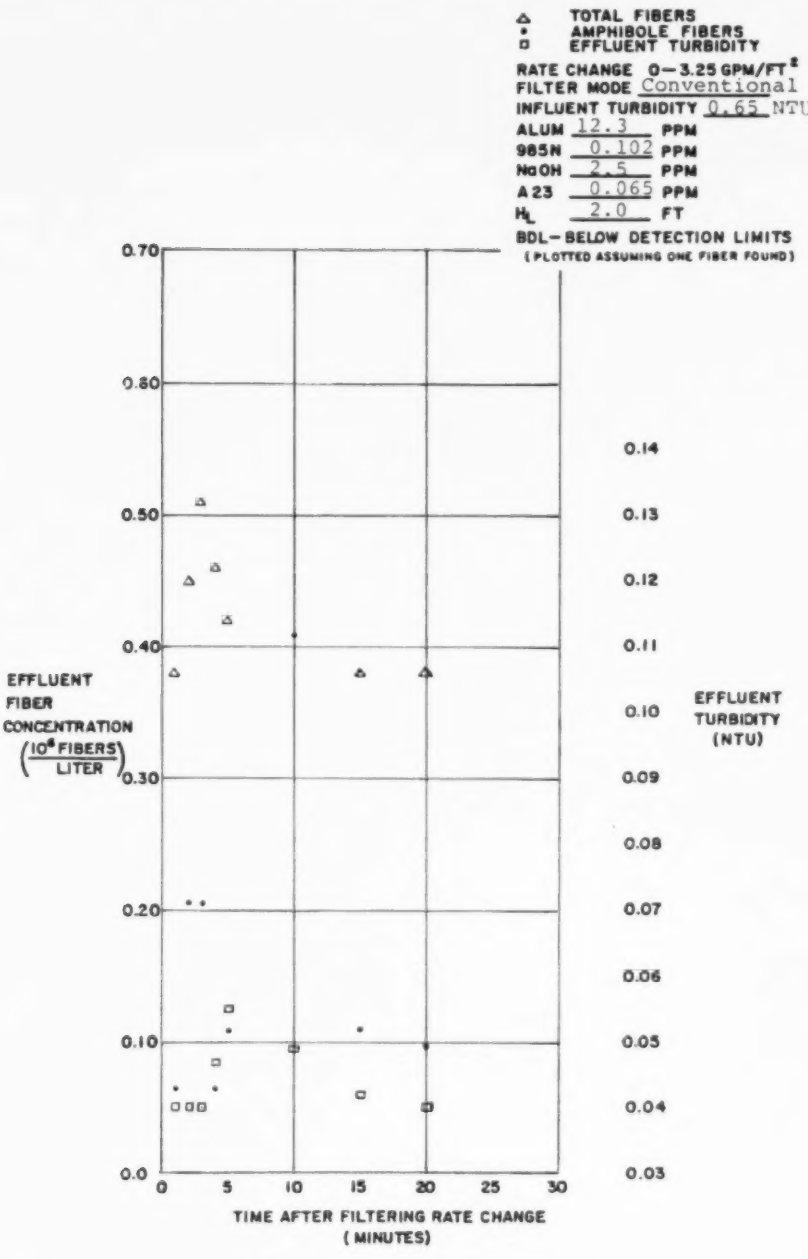
E. TEMPERATURE VS pH CURVES

APPENDIX A

FILTER RESTART STRESS

FILTER RESTART STRESS

RUN 1 JULY 6, 1977 FILTER NO. 1 (Dual Media)

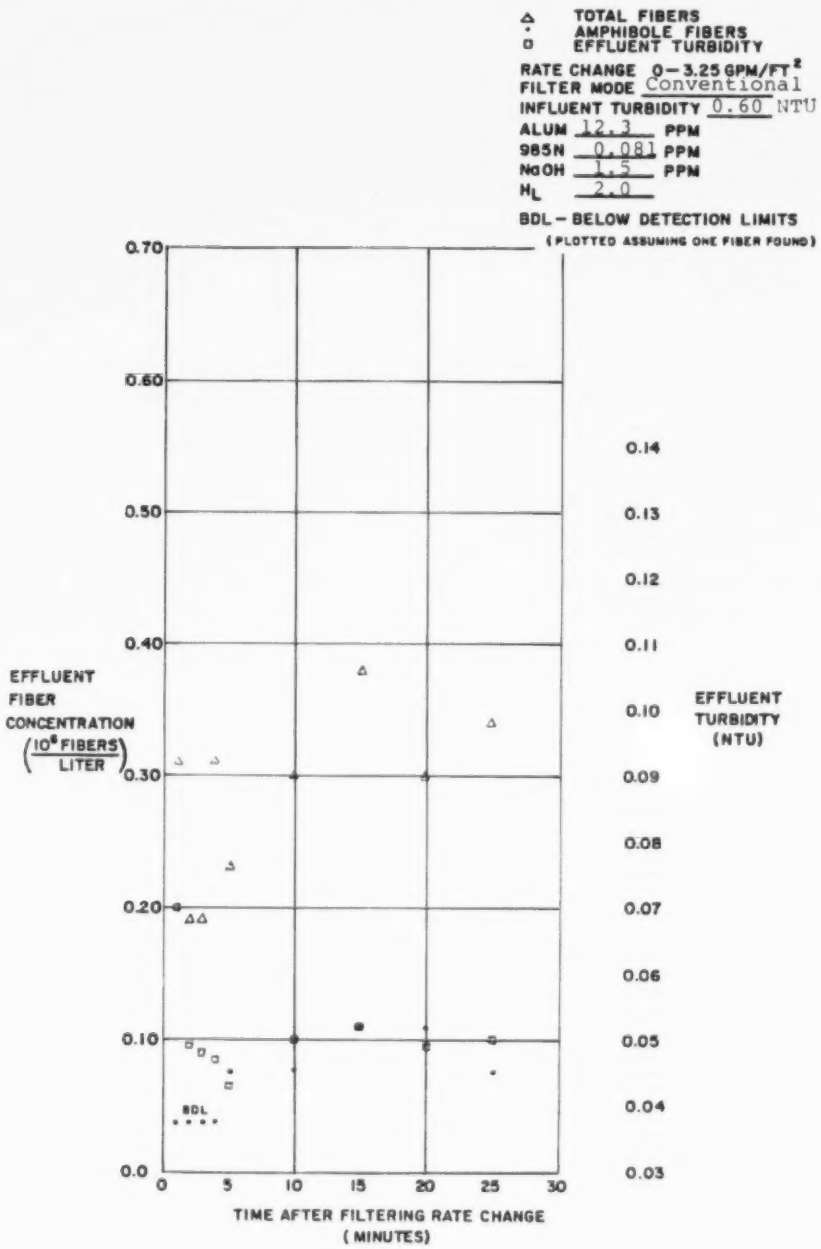


GRAPH 1

RUN 2

FILTER RESTART STRESS

AUGUST 10, 1977 FILTER NO. 2 (Mixed Media)



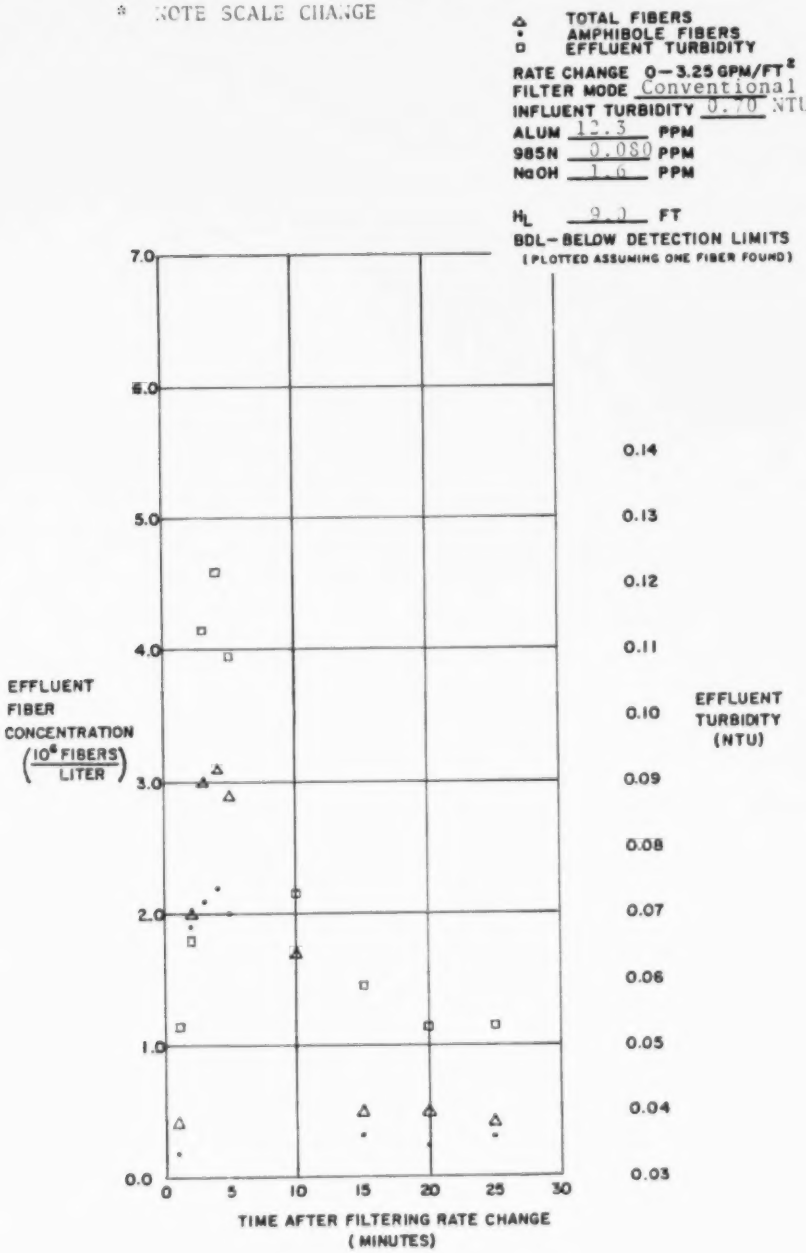
GRAPH 2

RUN 3

FILTER RESTART STRESS

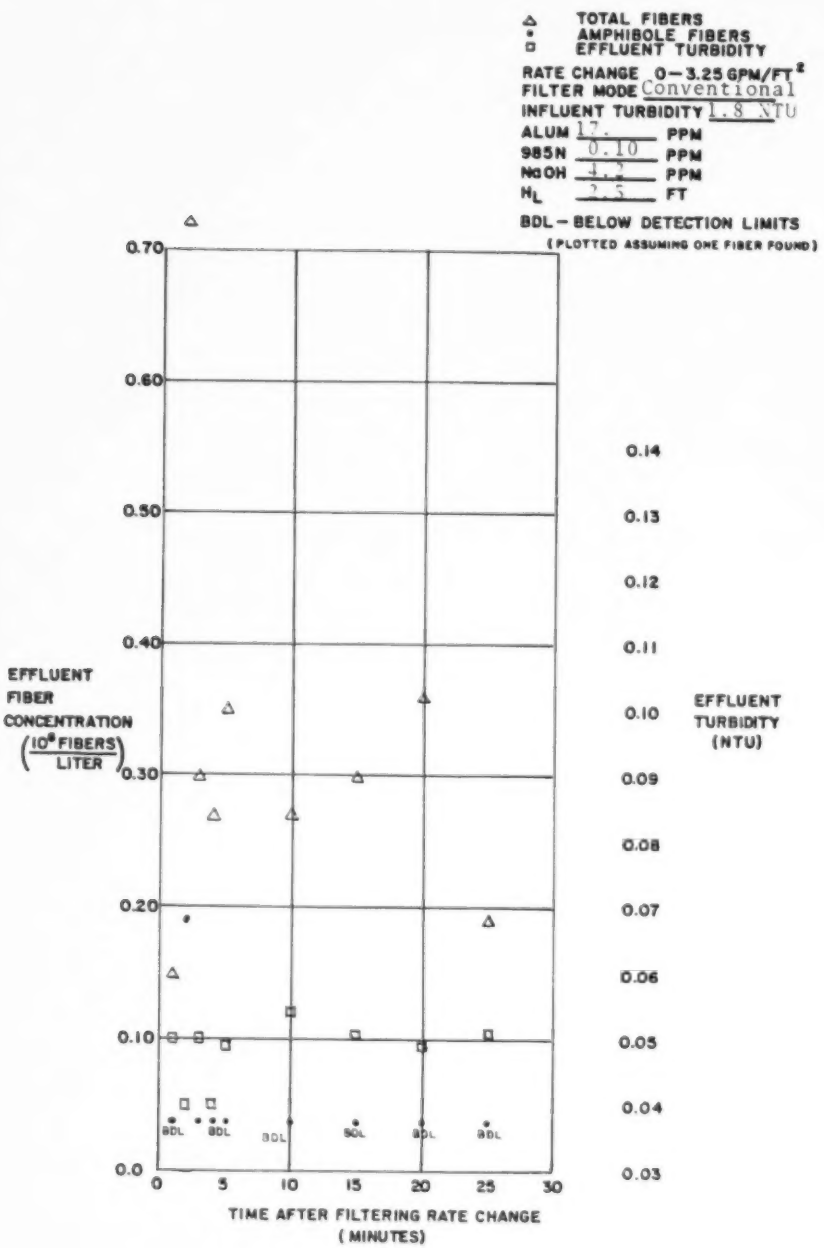
AUGUST 17, 1977 **FILTER NO.** 3 (Fixed Media)

* NOTE SCALE CHANGE



GRAPH 3

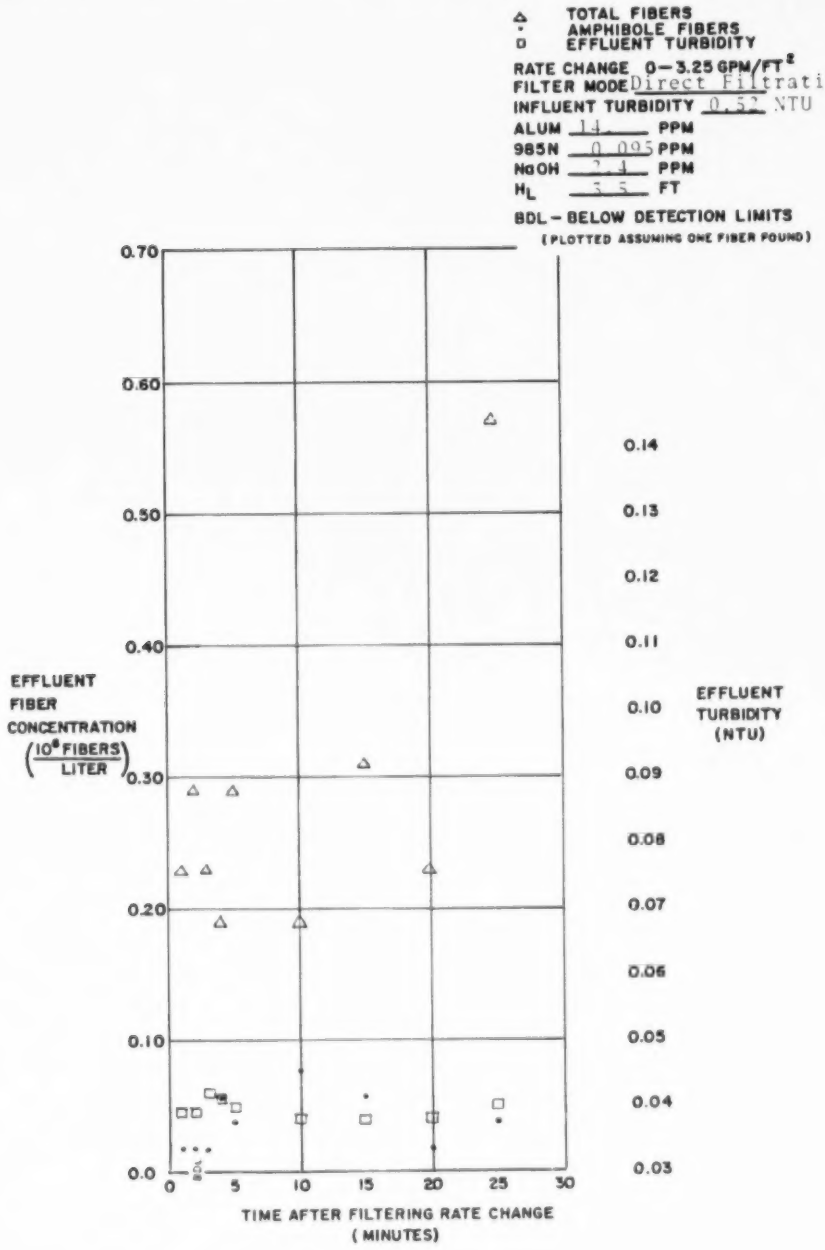
RUN 4 FILTER RESTART STRESS
SEPTEMBER 20, 1977 FILTER NO. 1 (Dual Media)



GRAPH 4

FILTER RESTART STRESS

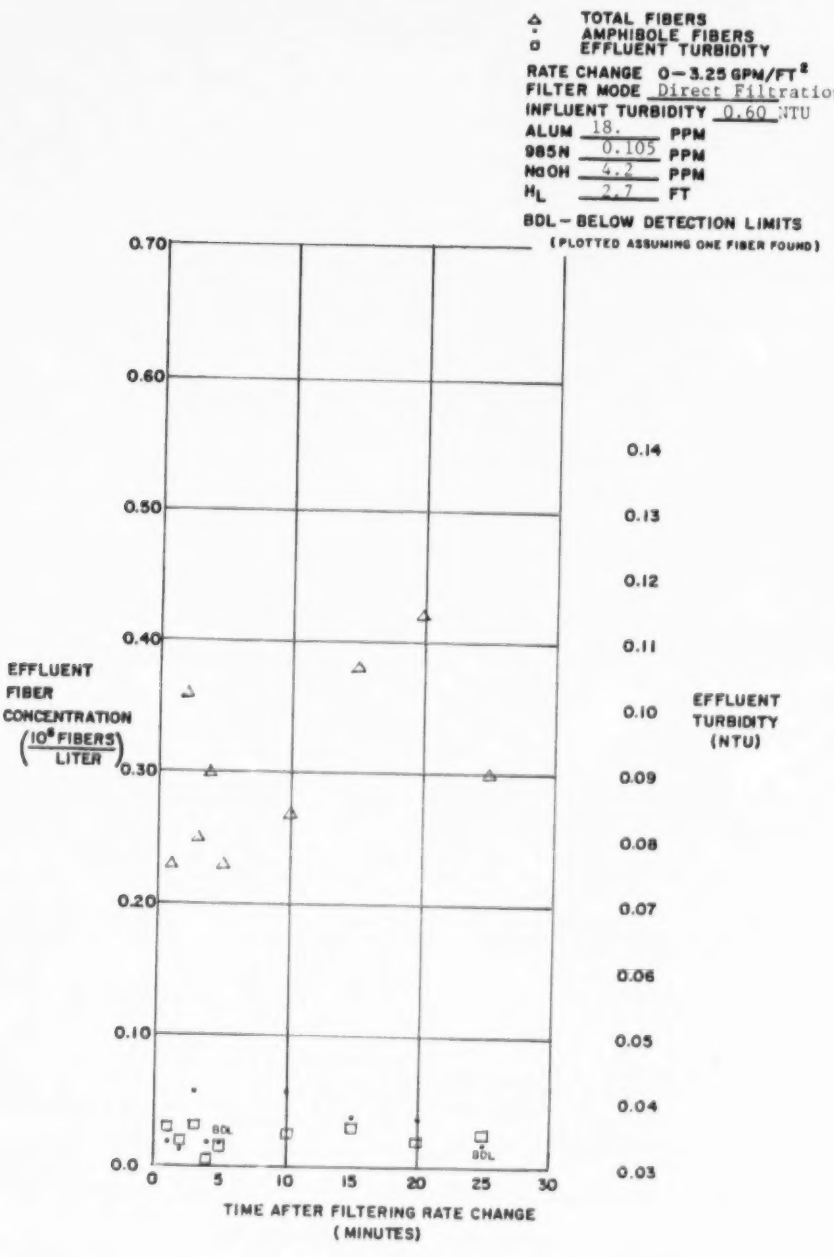
RUN 5 NOVEMBER 11, 1977 FILTER NO. 1 (Dual Media)



GRAPH 5

FILTER RESTART STRESS

RUN 6 NOVEMBER 22, 1977 **FILTER NO.** 3 (Mixed Media)



GRAPH 6

RUN 7

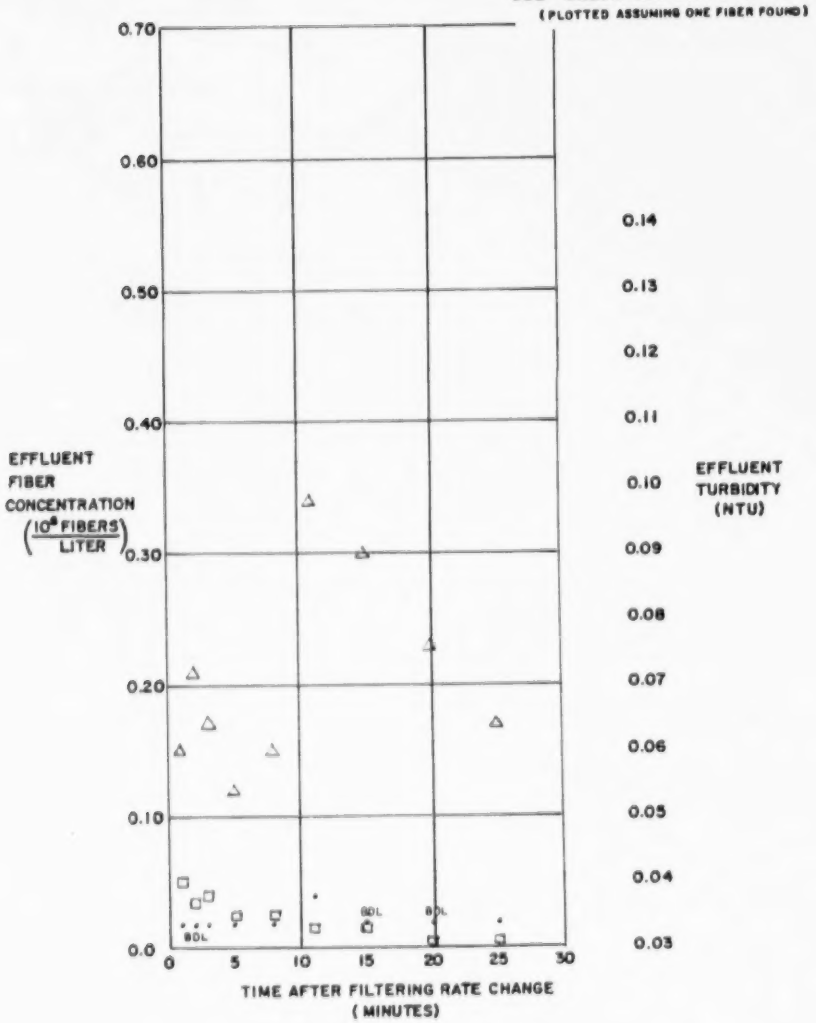
FILTER RESTART STRESS

NOVEMBER 28, 1977 FILTER NO. 2 (Mixed Media)

△ TOTAL FIBERS
• AMPHIBOLE FIBERS
□ EFFLUENT TURBIDITY

RATE CHANGE 0—3.25 GPM/FT^2
FILTER MODE Direct Filtration
INFLUENT TURBIDITY 0.47 NTU
ALUM 14. PPM
985N 0.095 PPM
NaOH 2.3 PPM
H_L 6.9 FT

BDL – BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)



GRAPH 7

FILTER RESTART STRESS

RUN 8 NOVEMBER 28, 1977 **FILTER NO.** 1 (Dual Media)

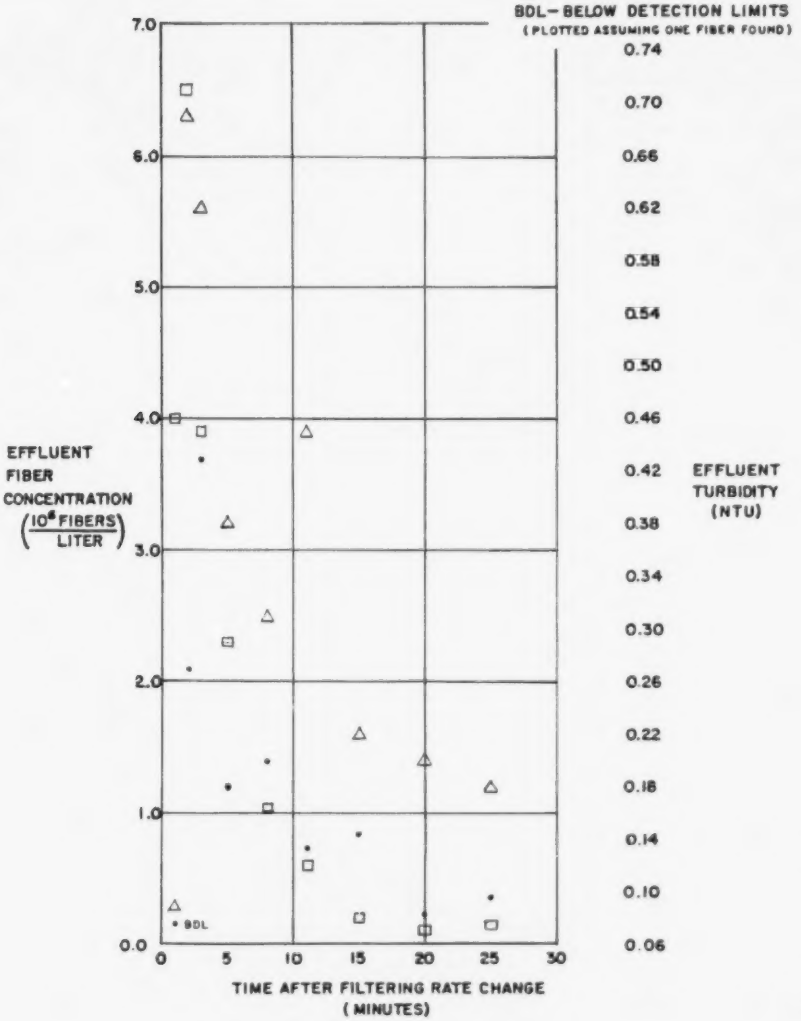
* Note scale change on fiber concentration & turbidity.

△ TOTAL FIBERS
• AMPHIBOLE FIBERS
□ EFFLUENT TURBIDITY

RATE CHANGE 0–3.25 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY 0.47 NTU
ALUM 14. PPM
985N 0.095 PPM
NaOH 2.3 PPM

H_L 9.0 FT

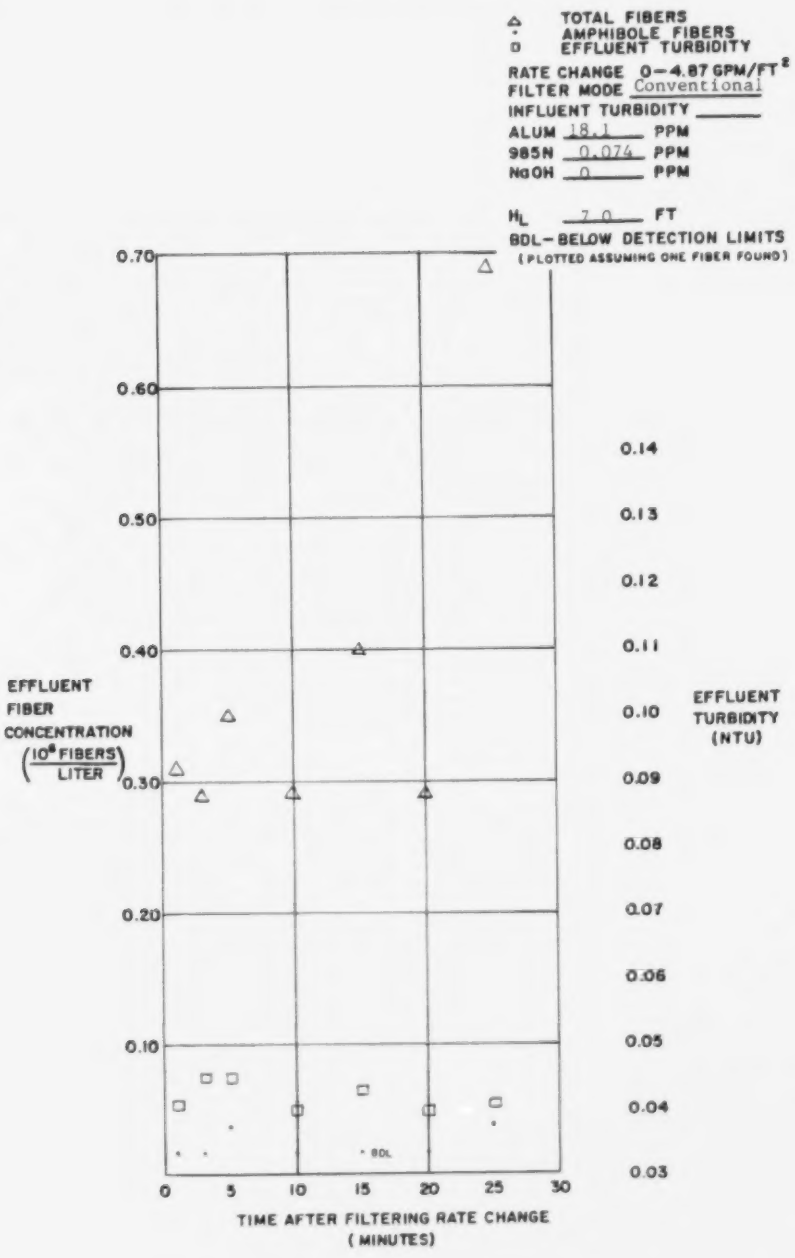
BDL–BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)



GRAPH 8

FILTER RESTART STRESS

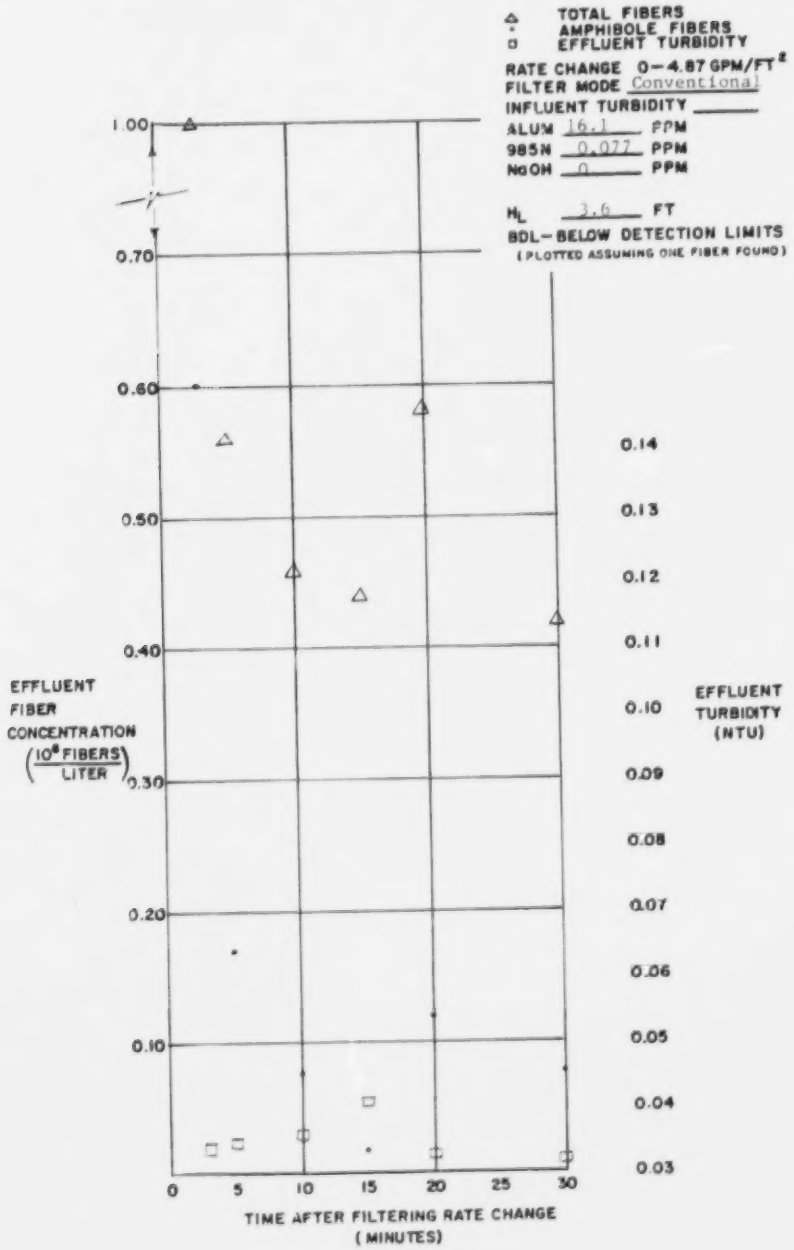
RUN 9 AUGUST 21, 1978 FILTER NO. 2 (Mixed Media)



GRAPH 9

FILTER RESTART STRESS

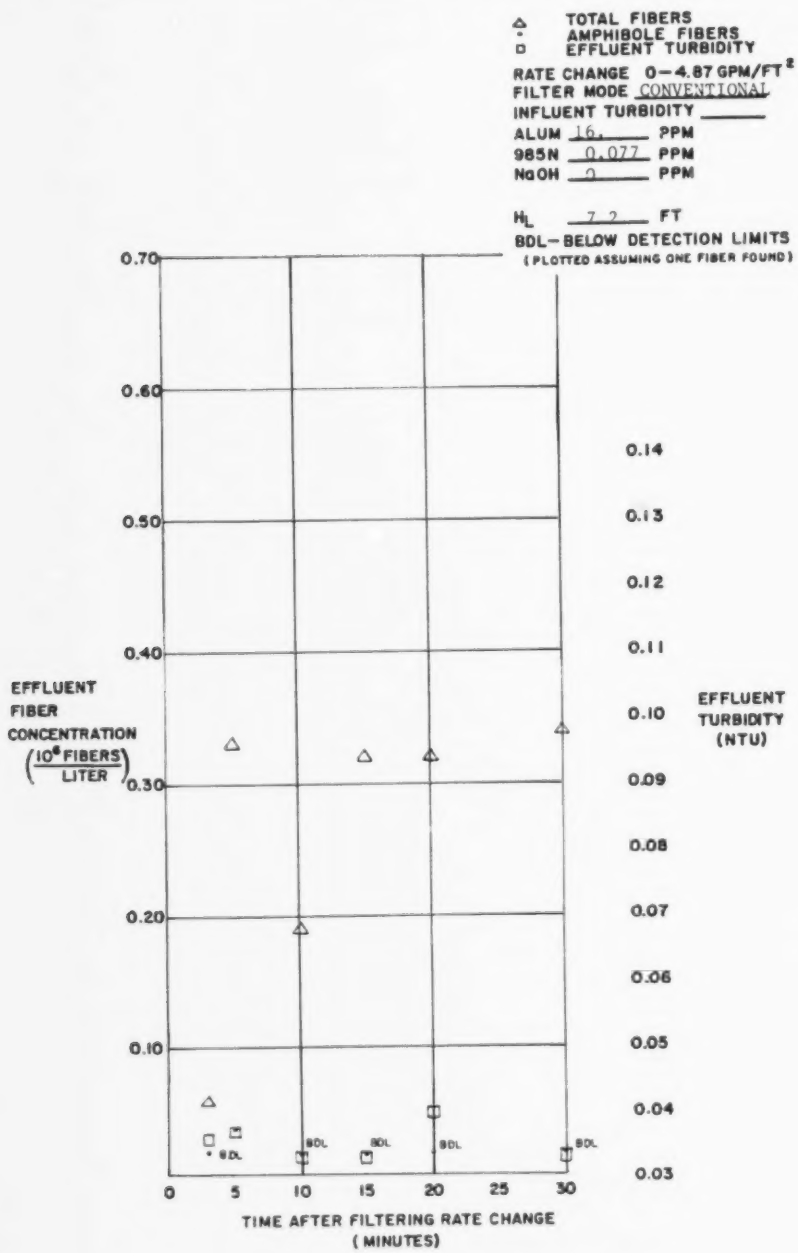
RUN 10 AUGUST 29, 1978 FILTER NO. 2 (Mixed Media)



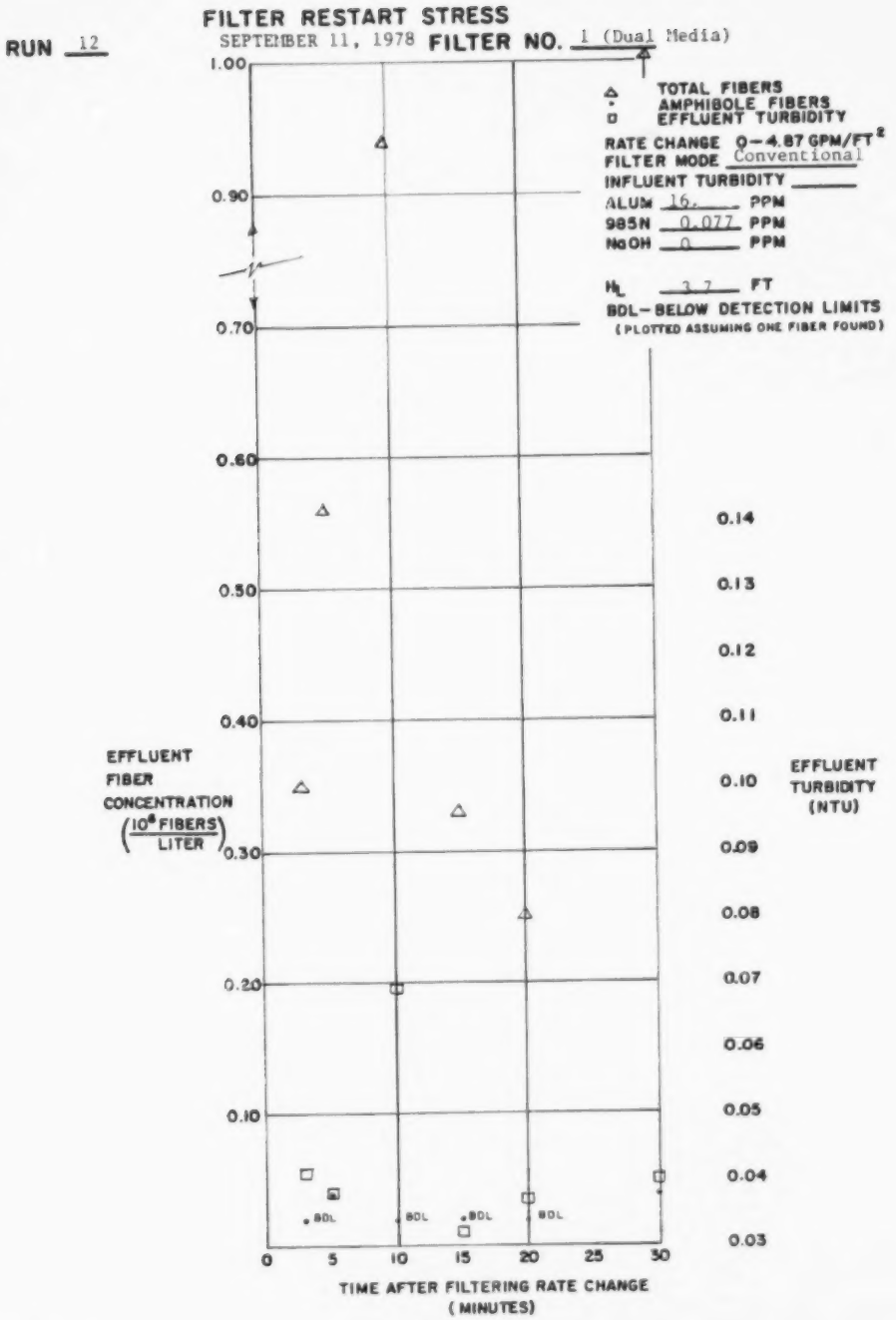
GRAPH 10

FILTER RESTART STRESS

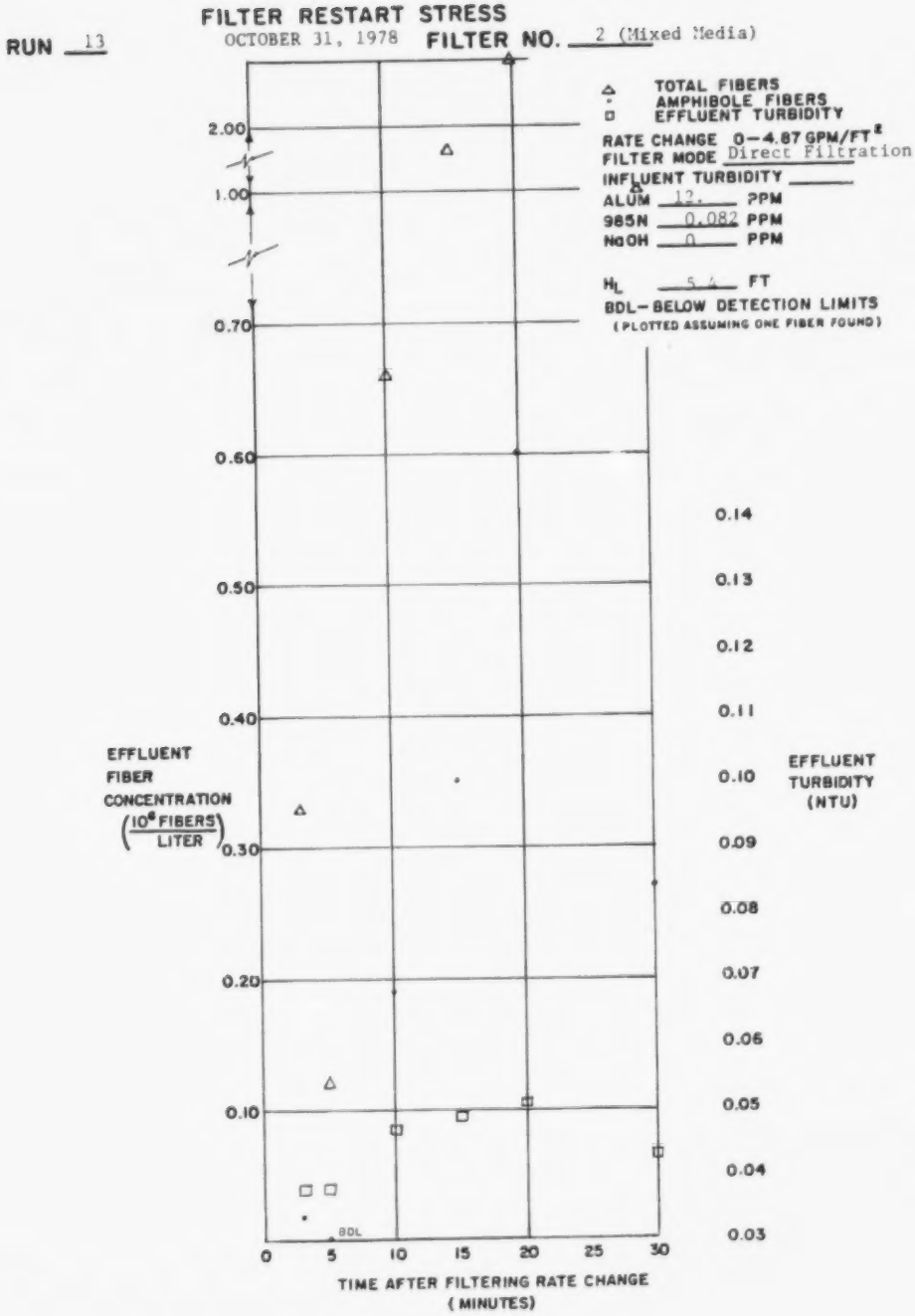
RUN 11 AUGUST 30, 1978 FILTER NO. 1 (Dual Media)



GRAPH 11


FILTER RESTART STRESS
RUN 12
SEPTEMBER 11, 1978 FILTER NO. 1 (Dual Media)
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 0-4.87 GPM/FT²
FILTER MODE Conventional
INFLUENT TURBIDITY
ALUM 16. PPM
985N 0.077 PPM
NaOH 0 PPM
H_L 3.7 FT
BDL-BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION (10^6 FIBERS/LITER)
EFFLUENT TURBIDITY (NTU)
1.00
0.90
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
BDL
0 5 10 15 20 25 30
TIME AFTER FILTERING RATE CHANGE
(MINUTES)

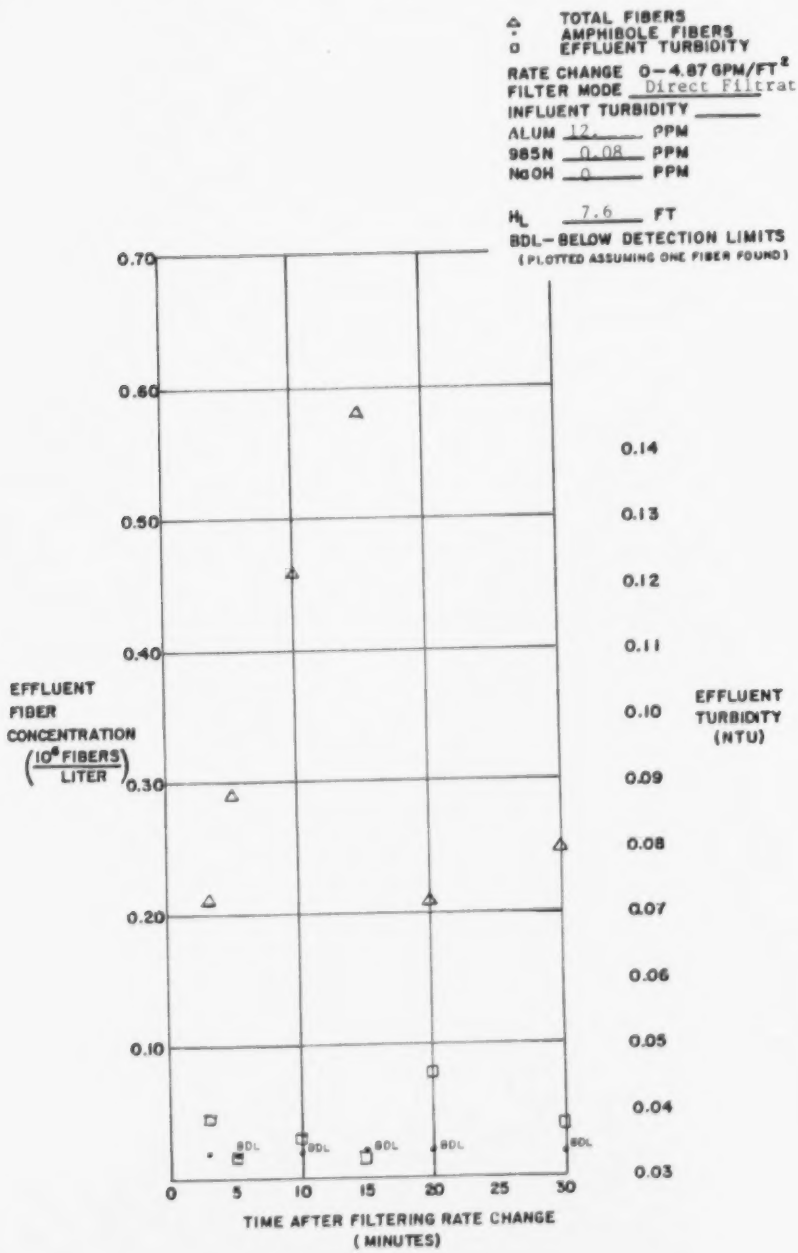
GRAPH 12


FILTER RESTART STRESS
RUN 13
OCTOBER 31, 1978 FILTER NO. 2 (Mixed Media)
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 0–4.87 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY
ALUM 12. PPM
985N 0.082 PPM
NaOH 0 PPM
H_L 5.4 FT
BDL–BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION ($\frac{10^6 \text{ FIBERS}}{\text{LITER}}$)
2.00
1.00
0.70
0.60
0.50
0.40
0.30
0.20
0.10
BDL
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
EFFLUENT TURBIDITY (NTU)
0
5
10
15
20
25
30
TIME AFTER FILTERING RATE CHANGE (MINUTES)

GRAPH 13

FILTER RESTART STRESS

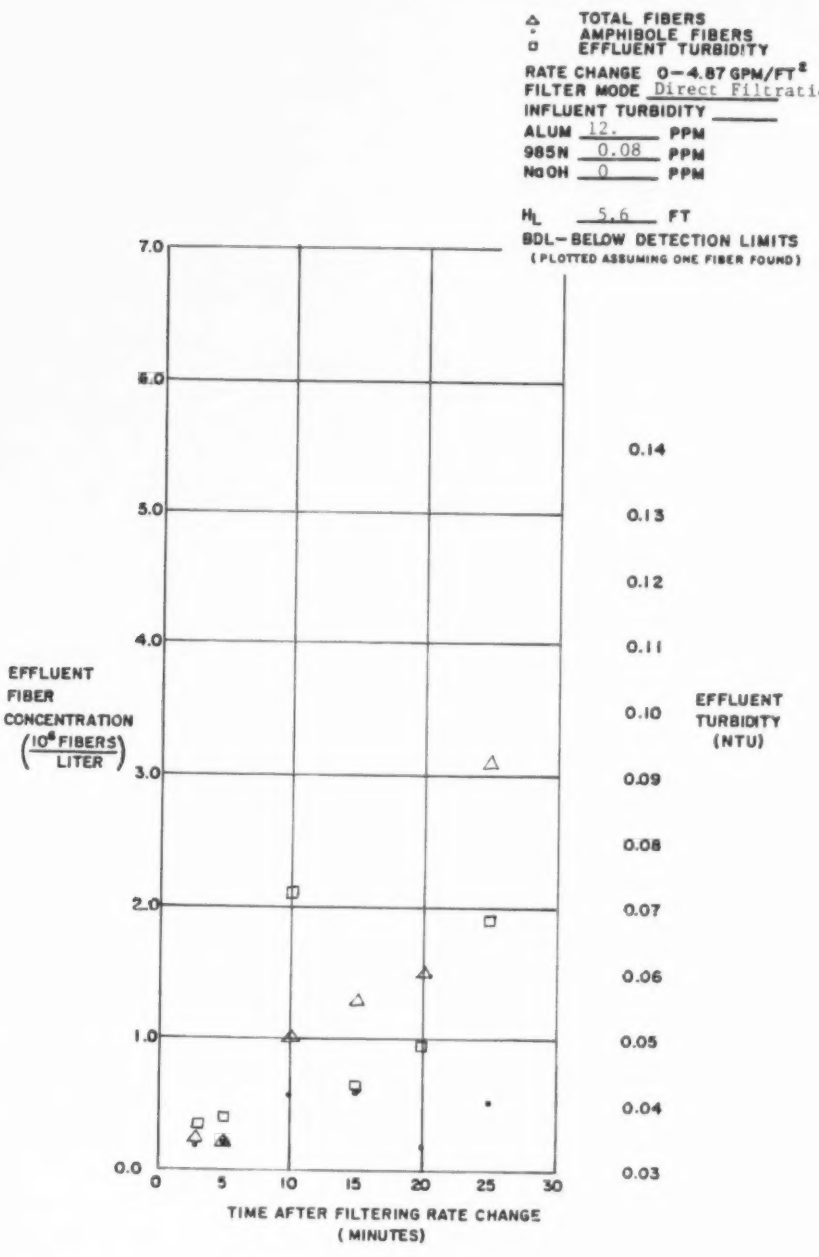
RUN 14 NOVEMBER 8, 1978 FILTER NO. 2 (Mixed Media)



GRAPH 14

FILTER RESTART STRESS

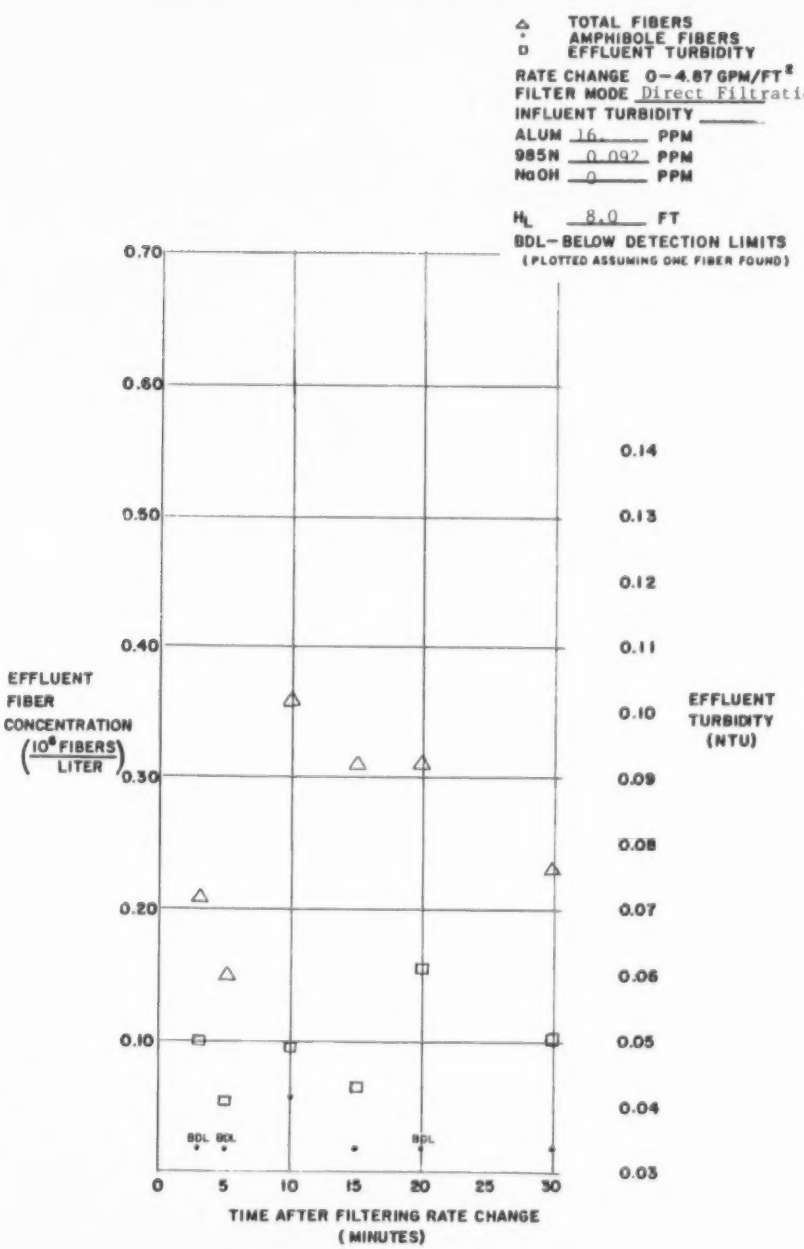
RUN 15 NOVEMBER 9, 1978 FILTER NO. 1 (Dual Media)



GRAPH 15

FILTER RESTART STRESS

RUN 16 NOVEMBER 14, 1978 FILTER NO. 1 (Dual Media)



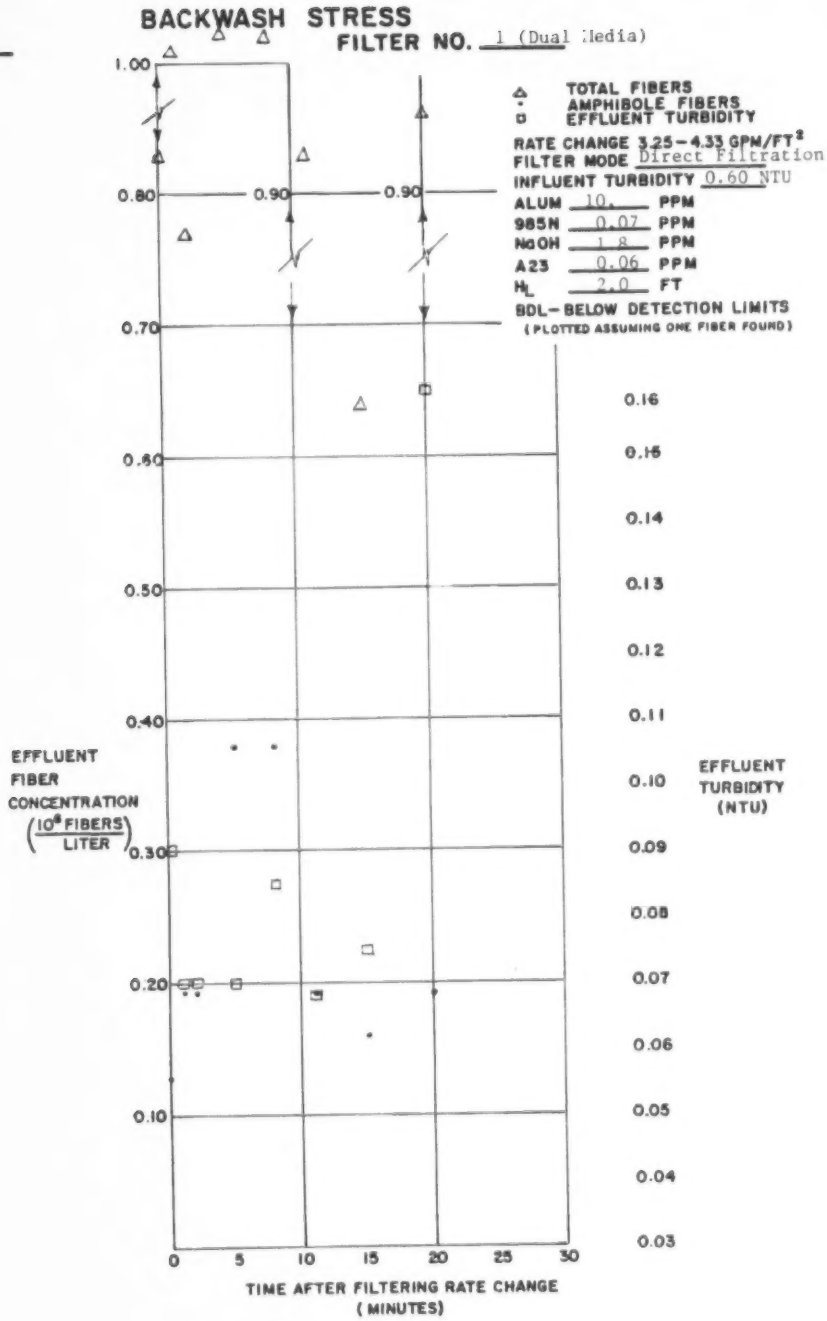
GRAPH 16

APPENDIX B

BACKWASH STRESS

RUN 1

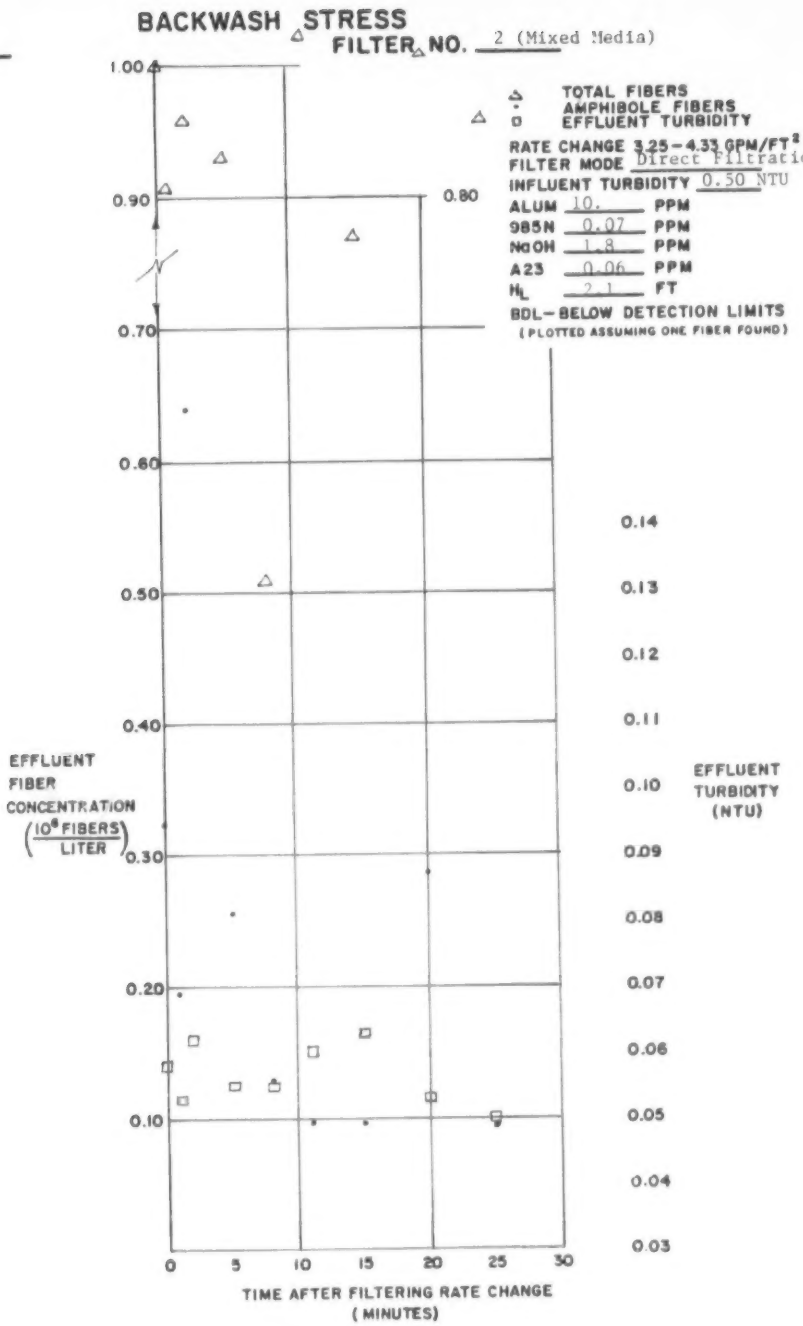
MAY 24, 1977



GRAPH 17

RUN 2

MAY 25, 1977

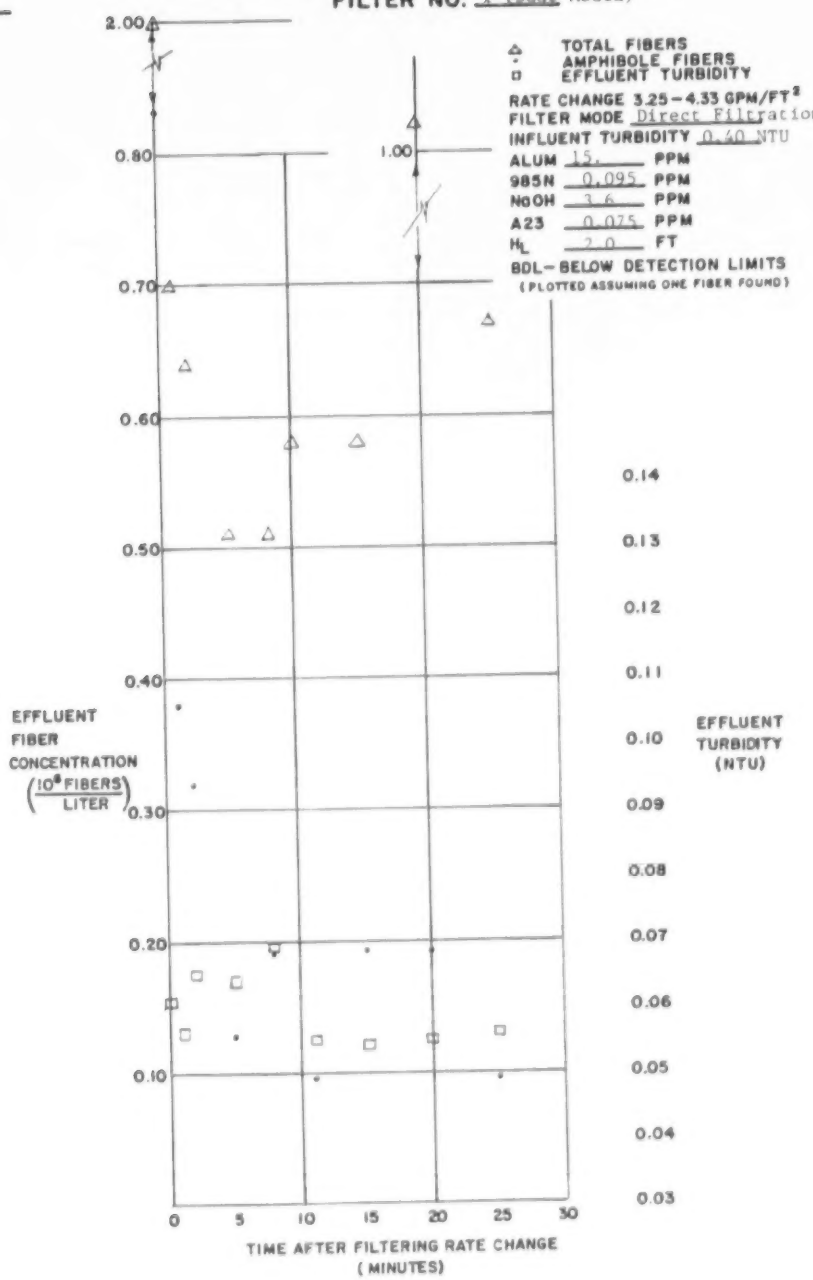


GRAPH 18

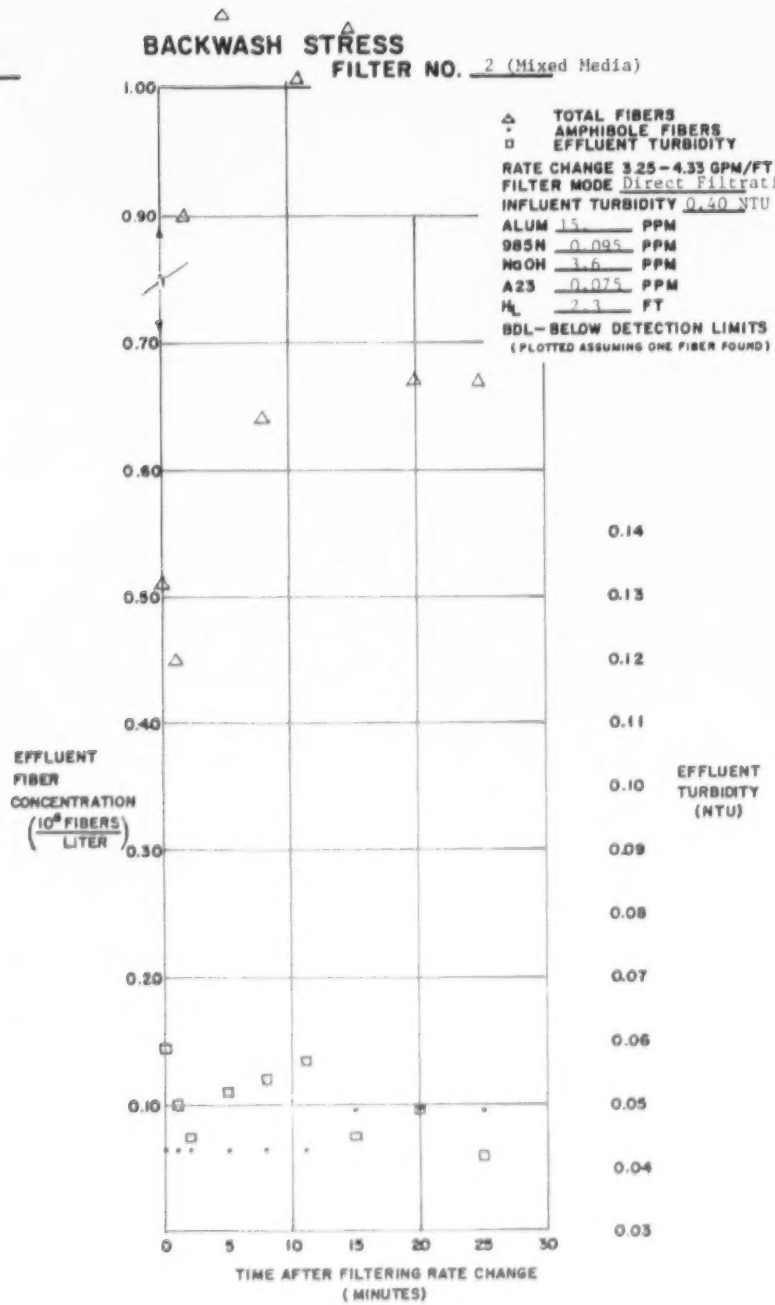
BACKWASH STRESS

RUN 3 FILTER NO. 1 (Dual Media)

JUNE 1, 1977



GRAPH 19

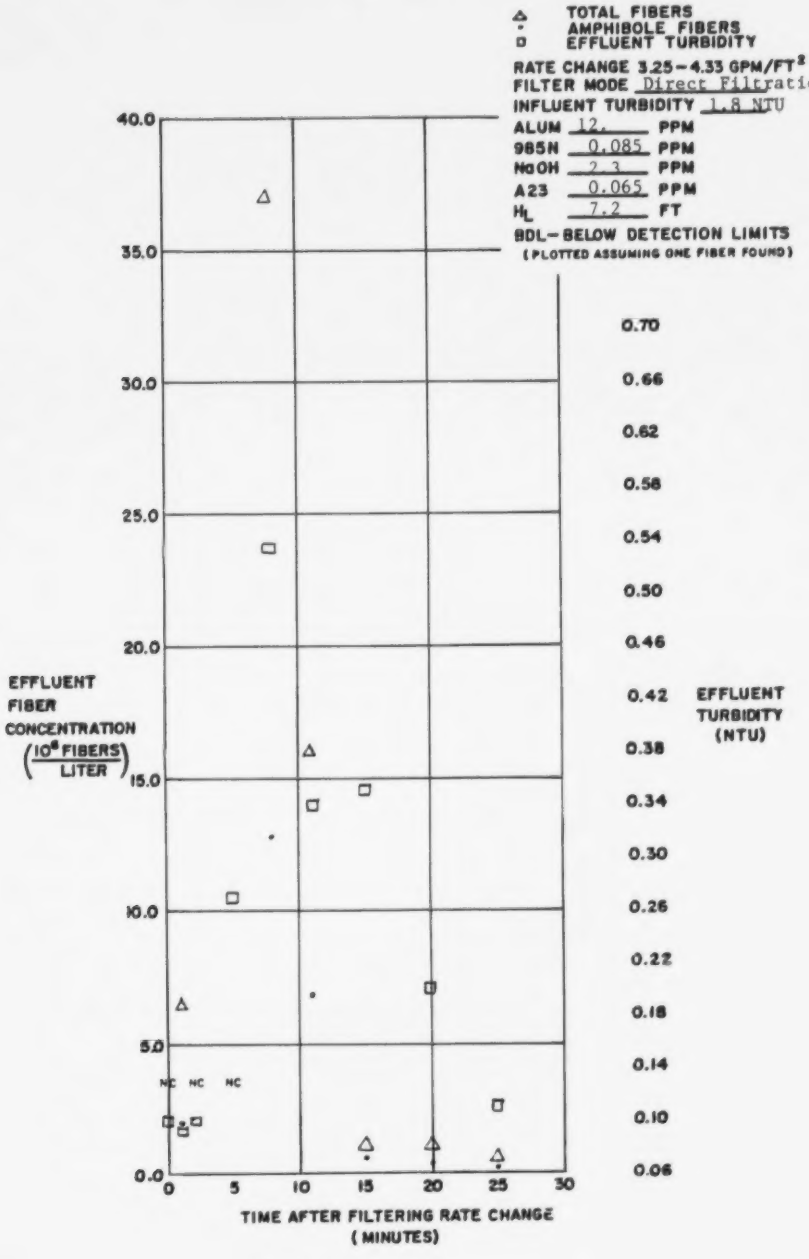

BACKWASH STRESS
RUN 4
FILTER NO. 2 (Mixed Media)
JUNE 2, 1977
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 3.25 – 4.33 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY 0.40 NTU
ALUM 15. PPM
985N 0.095 PPM
NaOH 3.6 PPM
A23 0.075 PPM
HL 2.3 FT
BDL – BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION (10⁶ FIBERS / LITER)
EFFLUENT TURBIDITY (NTU)
1.00
0.90
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0
5
10
15
20
25
30
TIME AFTER FILTERING RATE CHANGE (MINUTES)

GRAPH 20

RUN 5

BACKWASH STRESS

JUNE 9, 1977 FILTER NO. 1 (Dual Media)

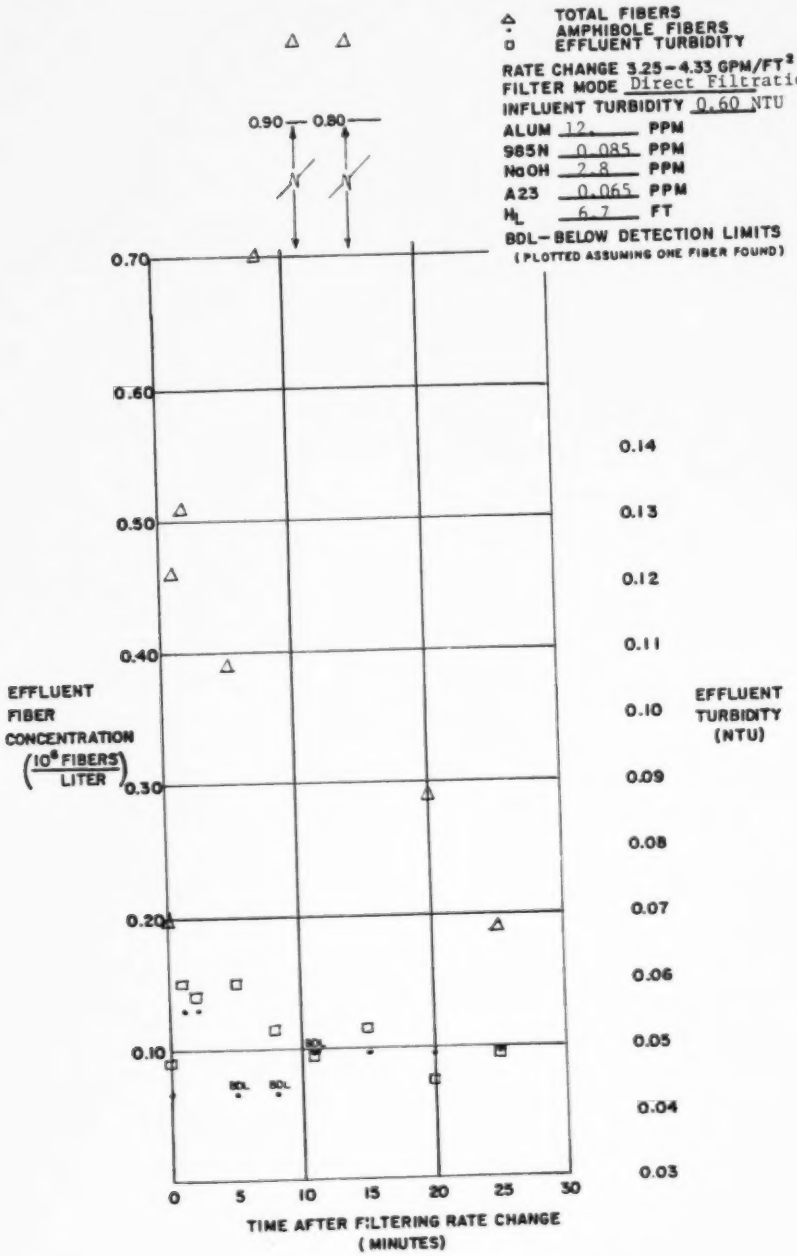


GRAPH 21

RUN 6

BACKWASH STRESS

JUNE 19, 1977 FILTER NO. 2 (Mixed Media)



GRAPH 22

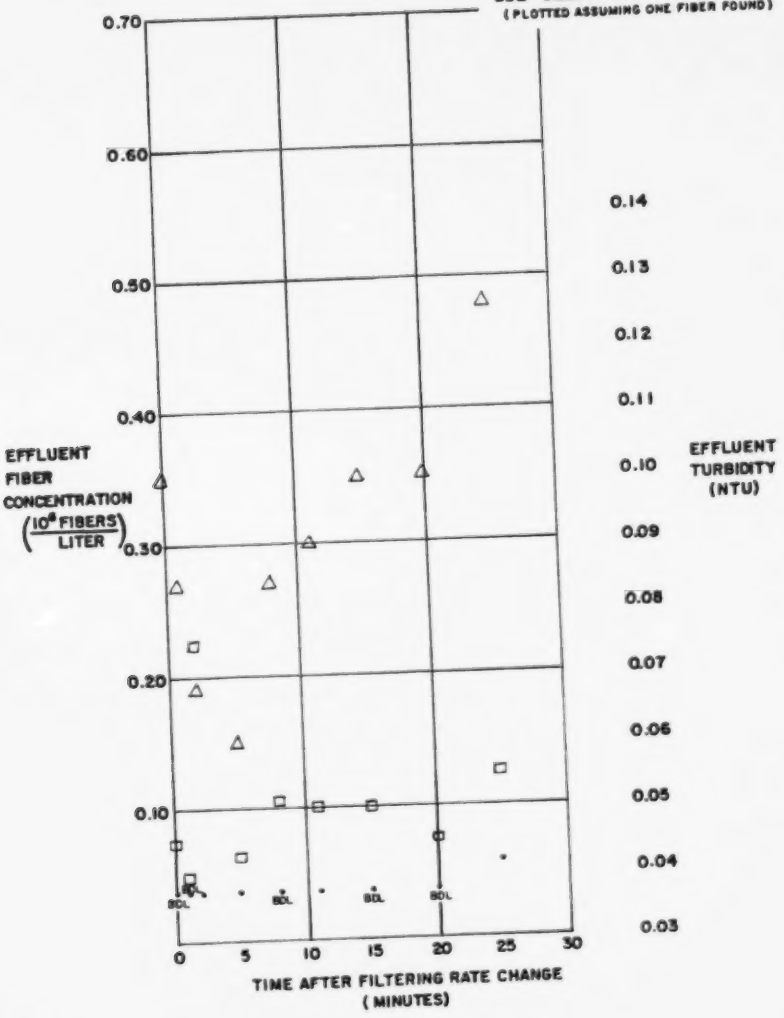
RUN 7

BACKWASH STRESS

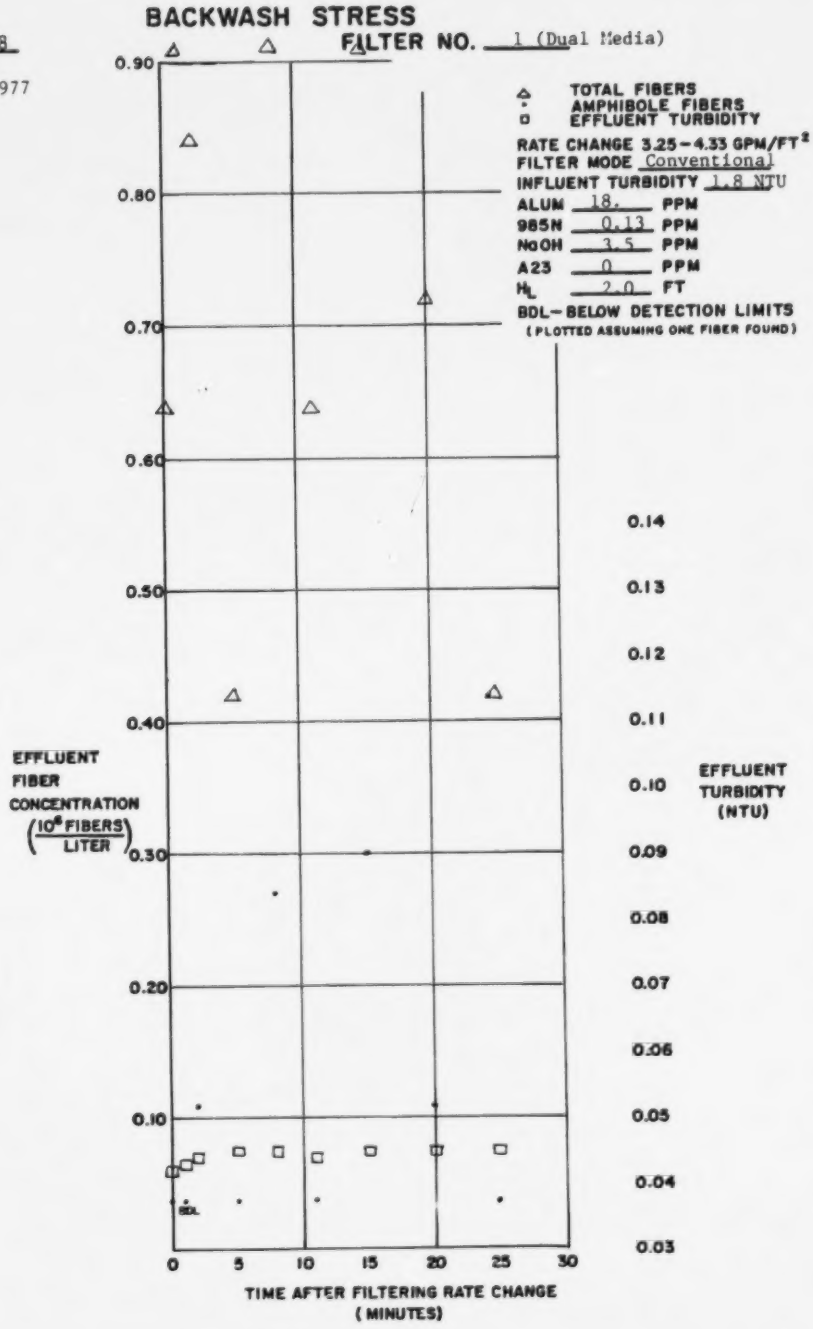
SEPTEMBER 28, 1977 FILTER NO. 1 (Dual Media)

△ TOTAL FIBERS
• AMPHIBOLE FIBERS
□ EFFLUENT TURBIDITY

RATE CHANGE 3.25-4.33 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY 1.3 NTU
ALUM 15. PPM
985N 0.125 PPM
NaOH 2.8 PPM
A23 _____ PPM
H_L 7.5 FT
BDL-BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)



GRAPH 23


BACKWASH STRESS
RUN 8
FILTER NO. 1 (Dual Media)
OCTOBER 4, 1977
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 3.25-4.33 GPM/FT²
FILTER MODE Conventional
INFLUENT TURBIDITY 1.8 NTU
ALUM 18. PPM
985N 0.13 PPM
NaOH 3.5 PPM
A23 0 PPM
HL 2.0 FT
BDL-BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION (10⁶ FIBERS / LITER)
EFFLUENT TURBIDITY (NTU)
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
BDL
0
5
10
15
20
25
30
TIME AFTER FILTERING RATE CHANGE (MINUTES)

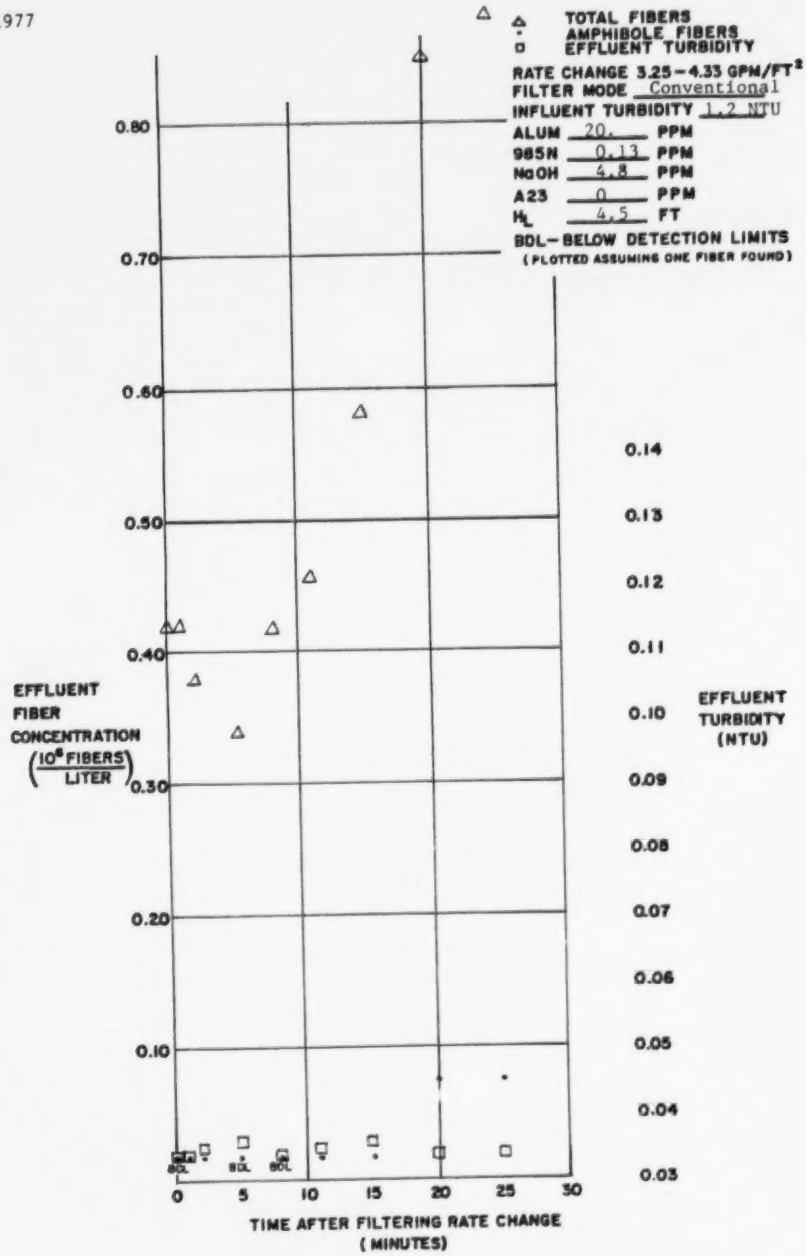
GRAPH 24

BACKWASH STRESS

RUN 9

FILTER NO. 4 (Mixed Media)

OCTOBER 14, 1977

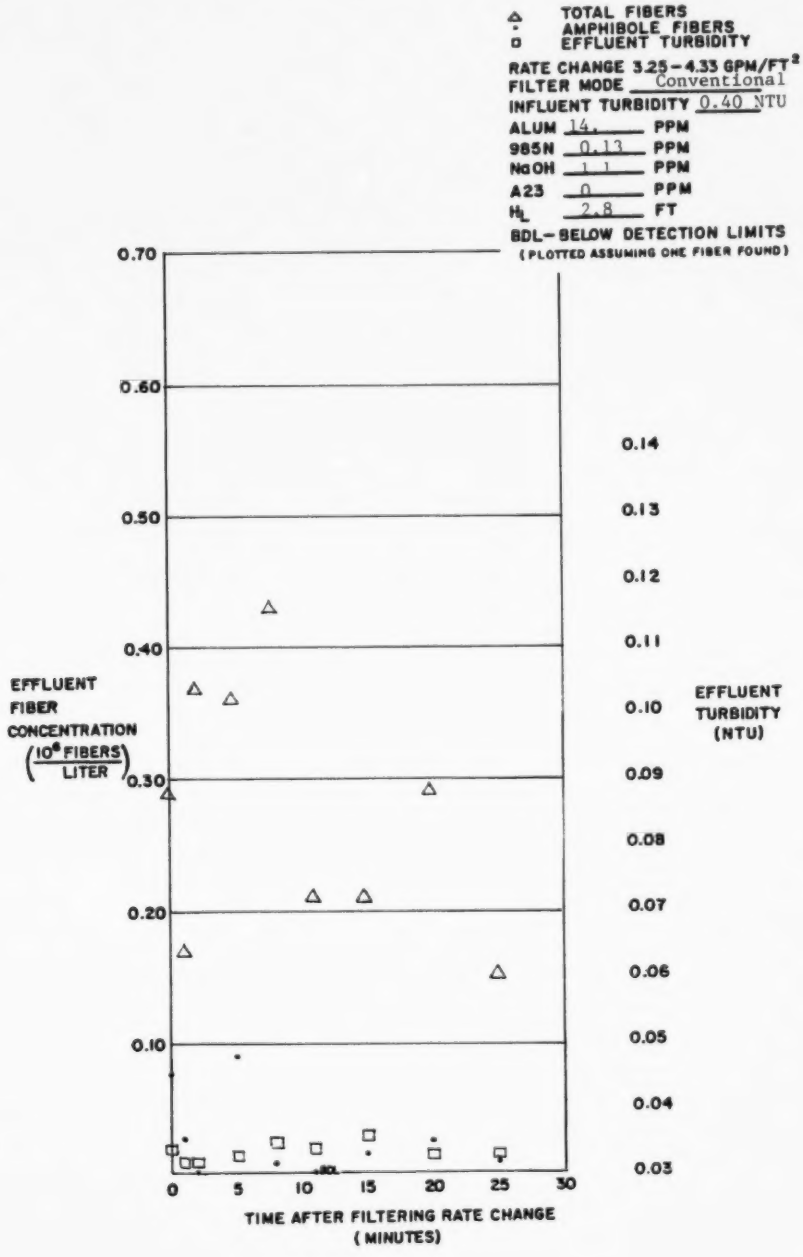


GRAPH 25

RUN 10

BACKWASH STRESS

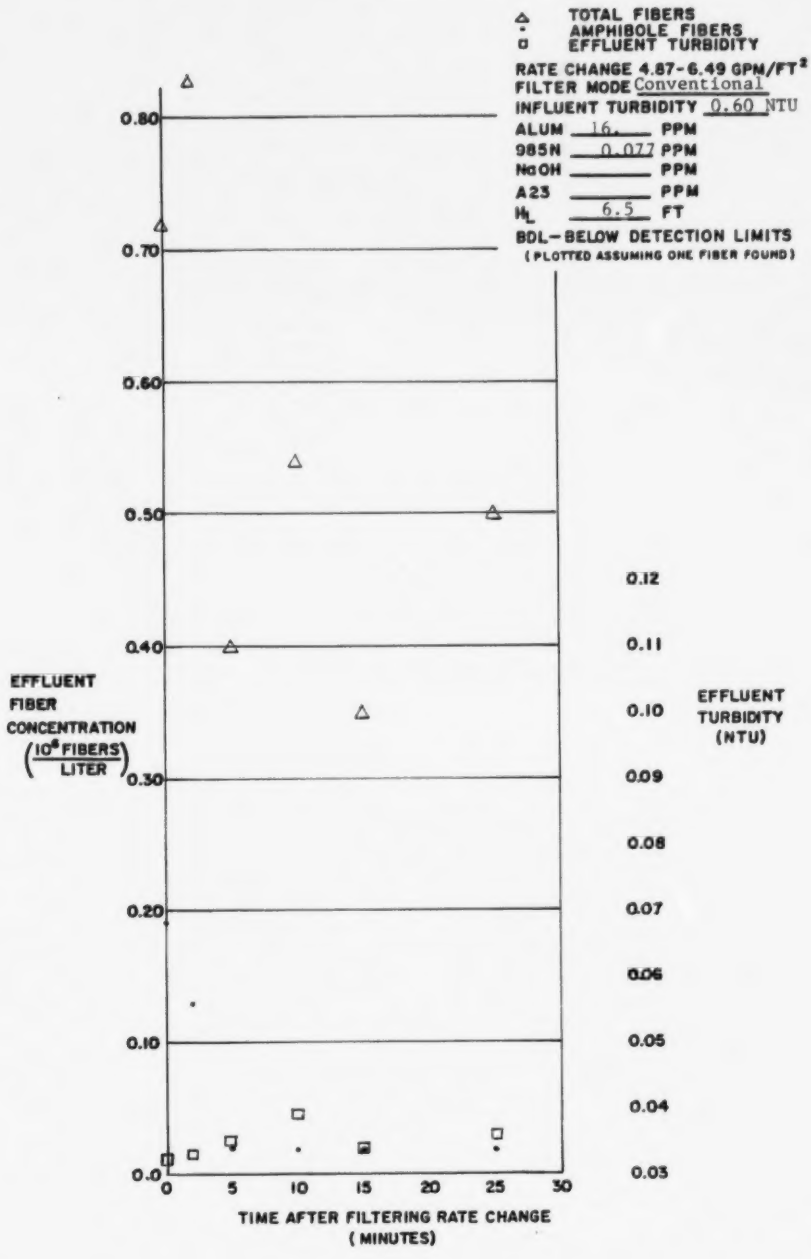
FEBRUARY 27, 1977 FILTER NO. 2 (Mixed Media)



GRAPH 26

BACKWASH STRESS

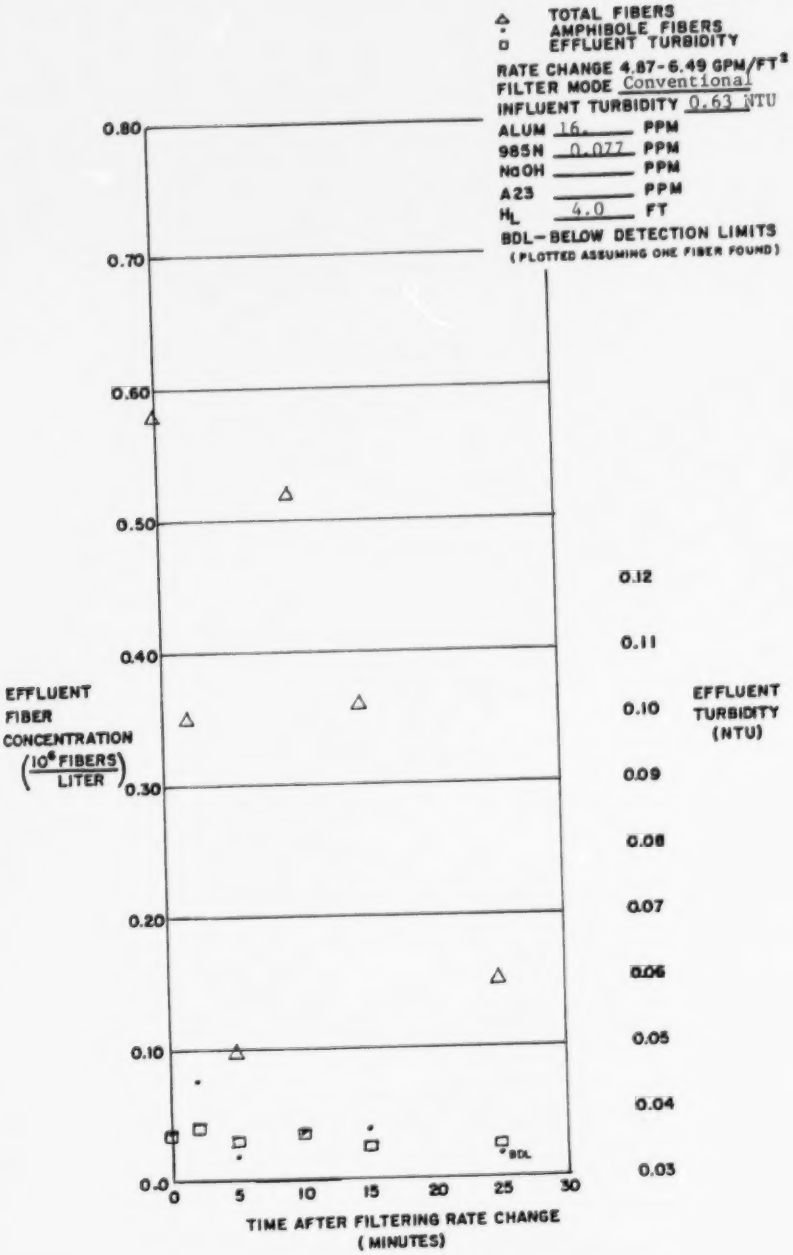
RUN 11 AUGUST 30, 1978 FILTER NO. 2



GRAPH 27

BACKWASH STRESS

RUN 12 AUGUST 28, 1978 FILTER NO. 2

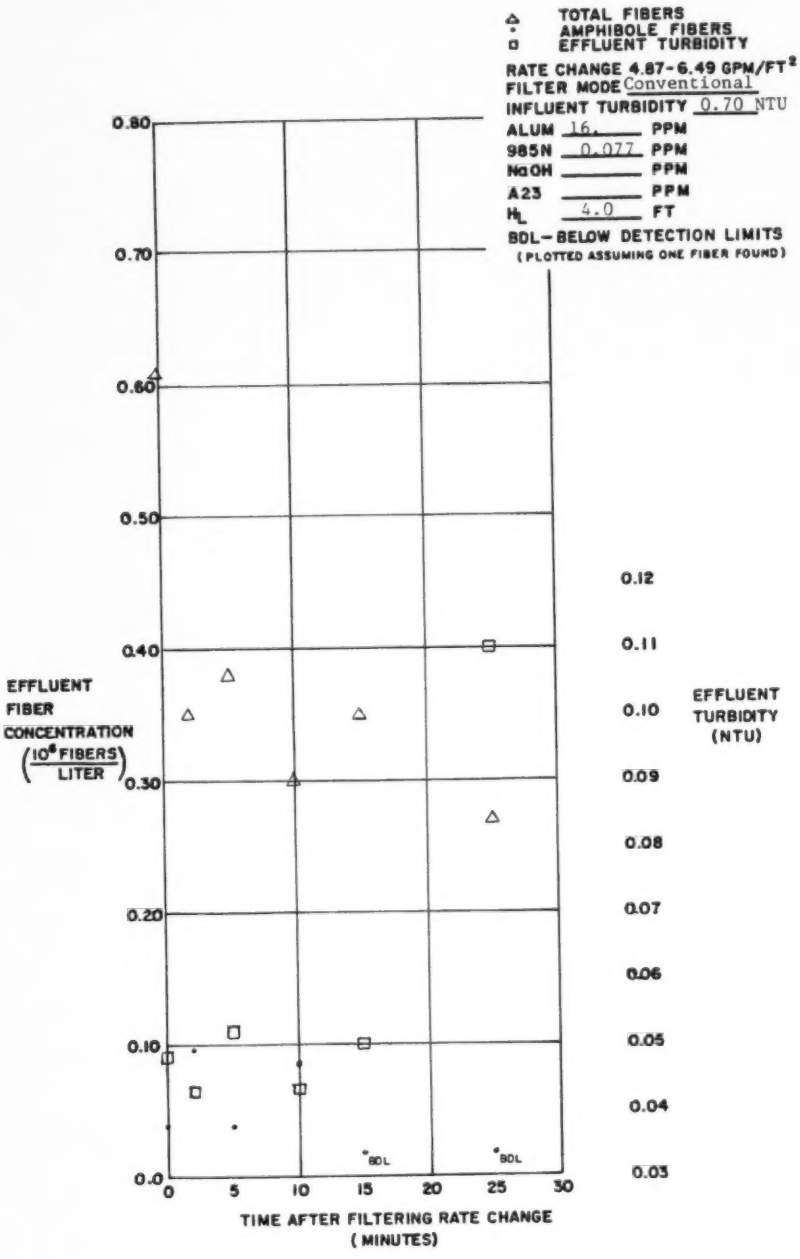


GRAPH 28

RUN 13

BACKWASH STRESS

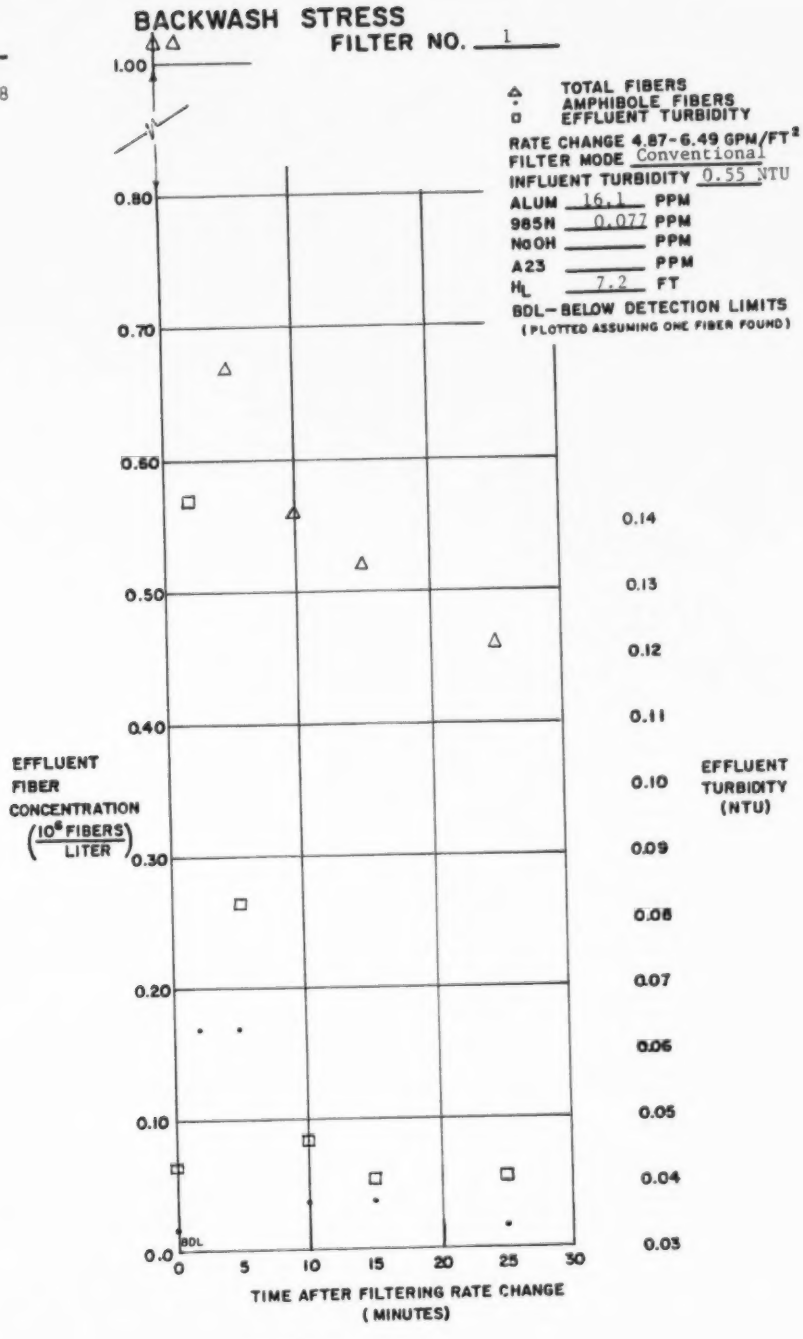
SEPTEMBER 5, 1978 FILTER NO. 1



GRAPH 29

RUN 14

SEPTEMBER 6, 1978

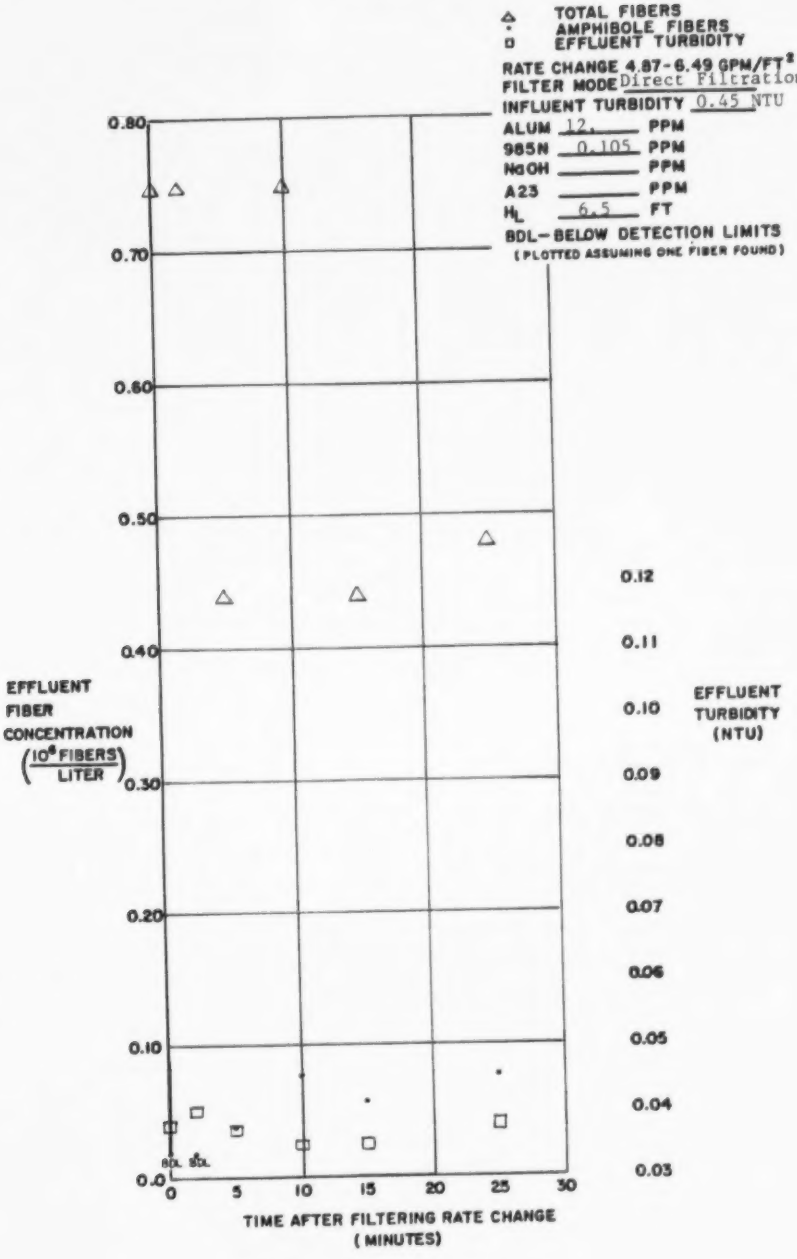


GRAPH 30

RUN 15

BACKWASH STRESS

OCTOBER 27, 1978 FILTER NO. 2

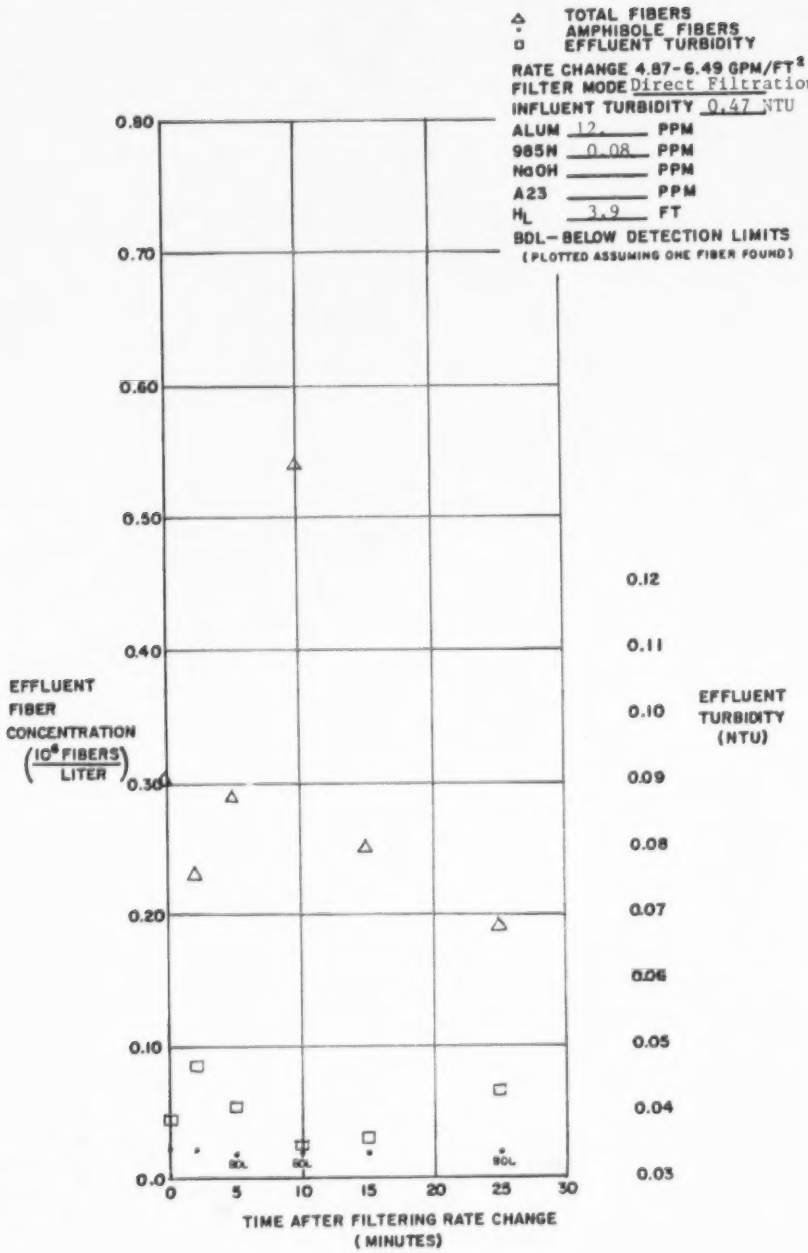


GRAPH 31

RUN 16

BACKWASH STRESS

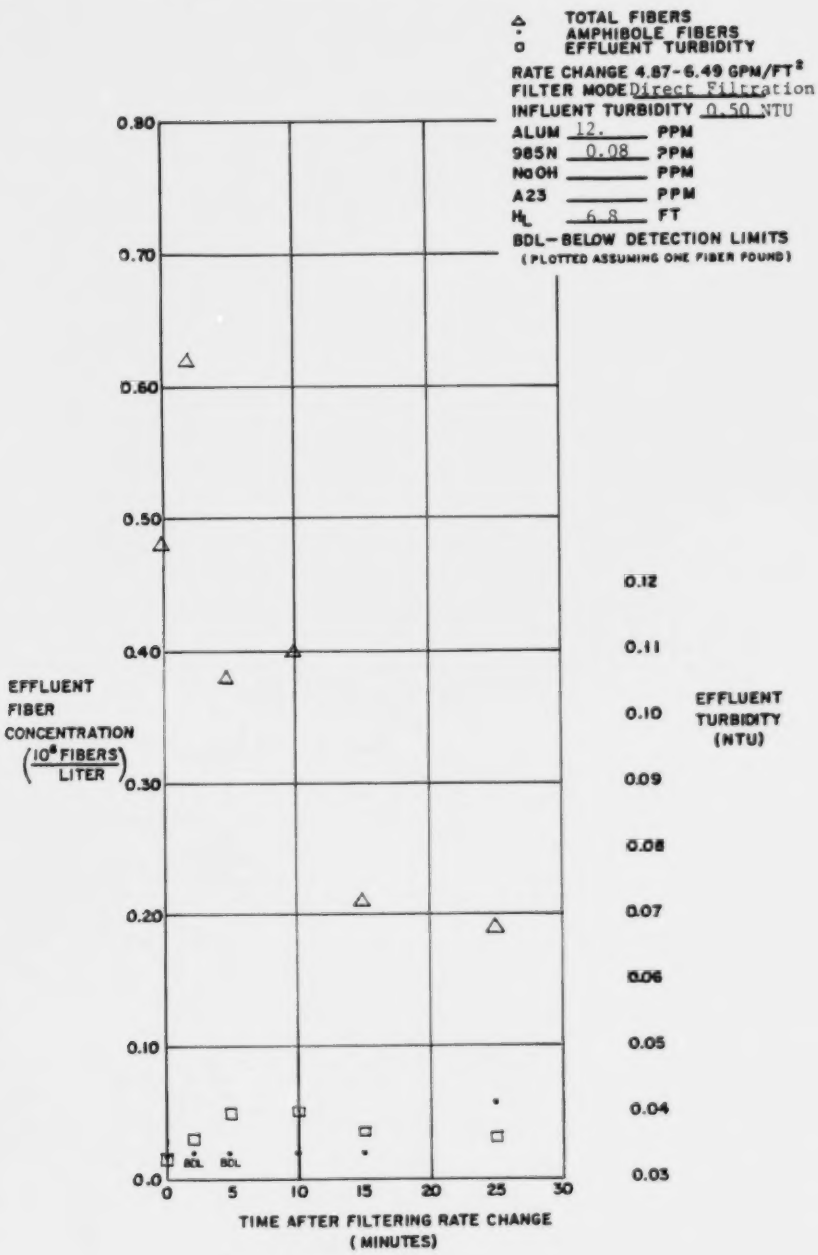
NOVEMBER 7, 1978 FILTER NO. 2



GRAPH 32

BACKWASH STRESS

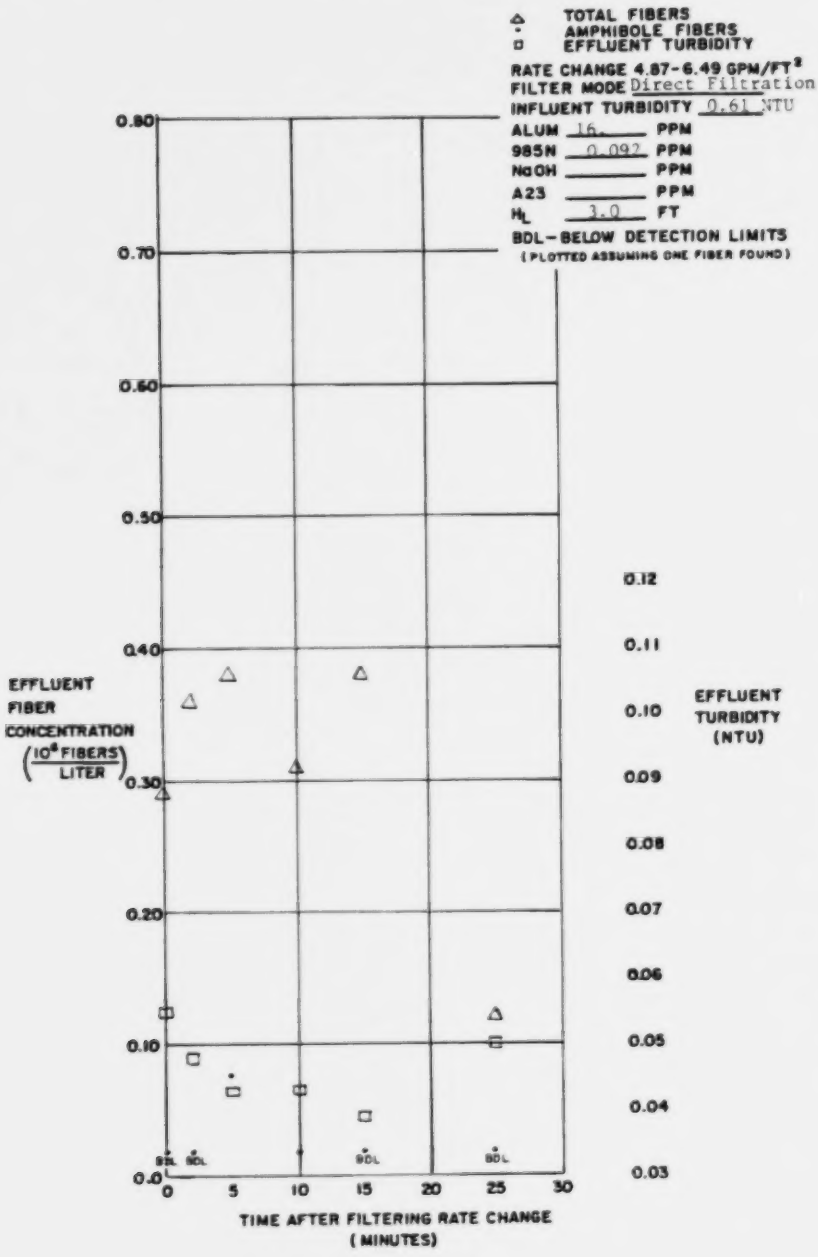
RUN 17 NOVEMBER 9, 1978 FILTER NO. 1



GRAPH 33

BACKWASH STRESS

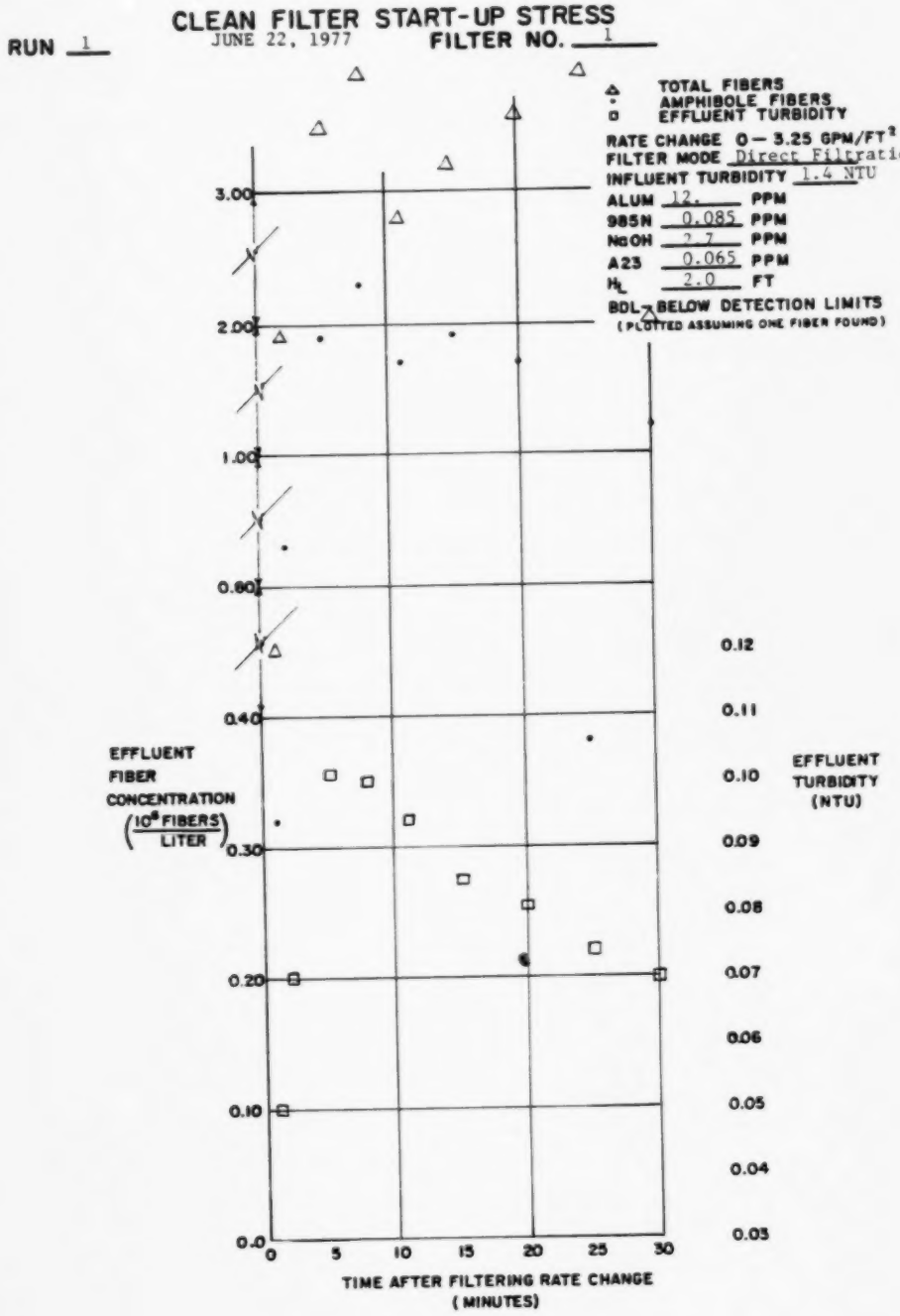
RUN 18 NOVEMBER 14, 1978 FILTER NO. 1



GRAPH 34

APPENDIX C

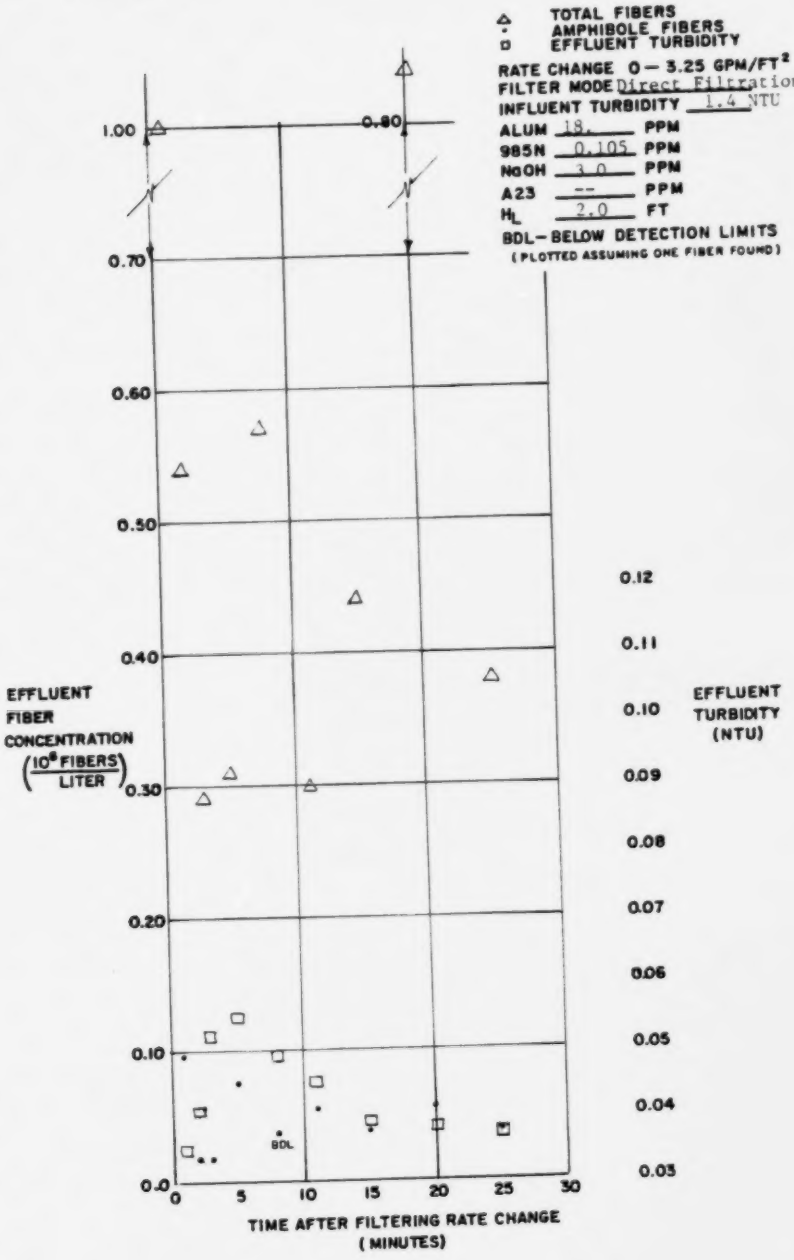
CLEAN FILTER START-UP STRESS


CLEAN FILTER START-UP STRESS
RUN 1
JUNE 22, 1977
FILTER NO. 1
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 0 — 3.25 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY 1.4 NTU
ALUM 12. PPM
985N 0.085 PPM
NaOH 2.7 PPM
A23 0.065 PPM
H_L 2.0 FT
BDL = BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION (10⁶ FIBERS/LITER)
EFFLUENT TURBIDITY (NTU)
3.00
2.00
1.00
0.60
0.40
0.30
0.20
0.10
0.0
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0
5
10
15
20
25
30
TIME AFTER FILTERING RATE CHANGE (MINUTES)

GRAPH 35

CLEAN FILTER START-UP STRESS

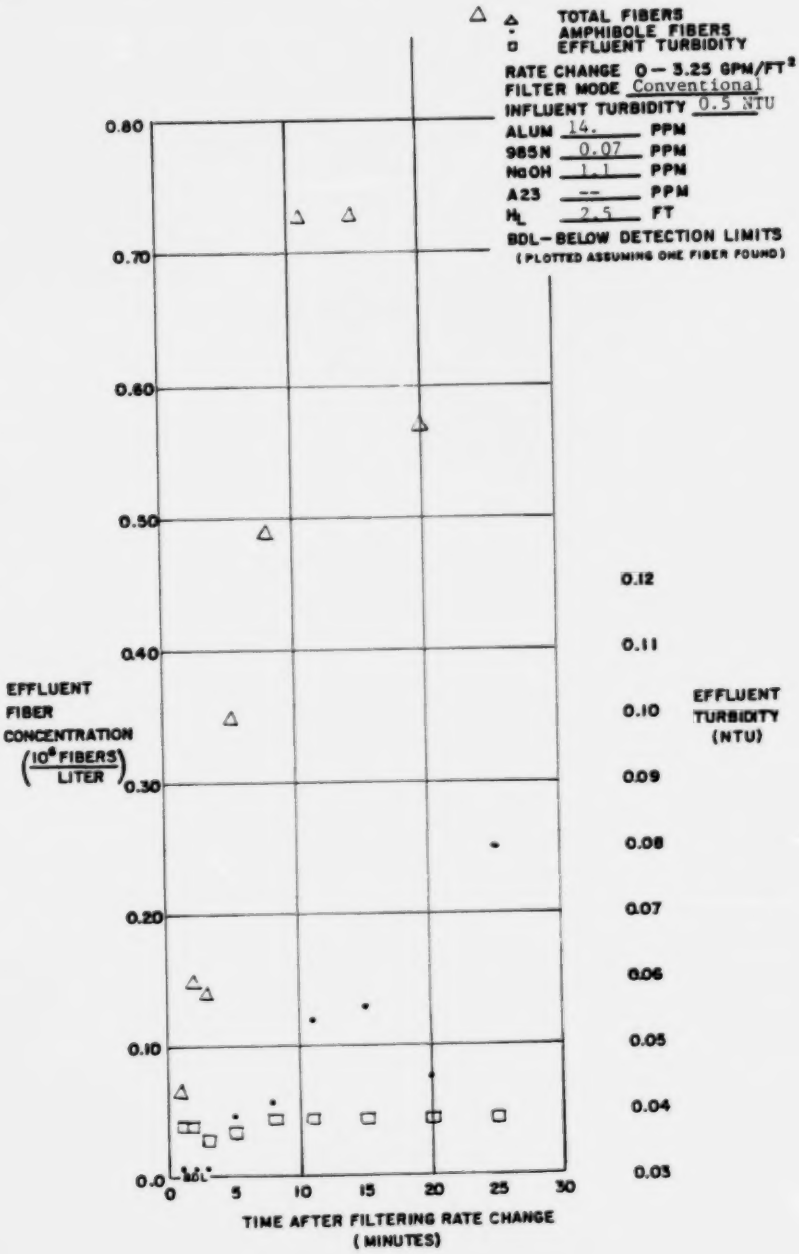
RUN 2 NOVEMBER 23, 1977 FILTER NO. 3



GRAPH 36

CLEAN FILTER START-UP STRESS

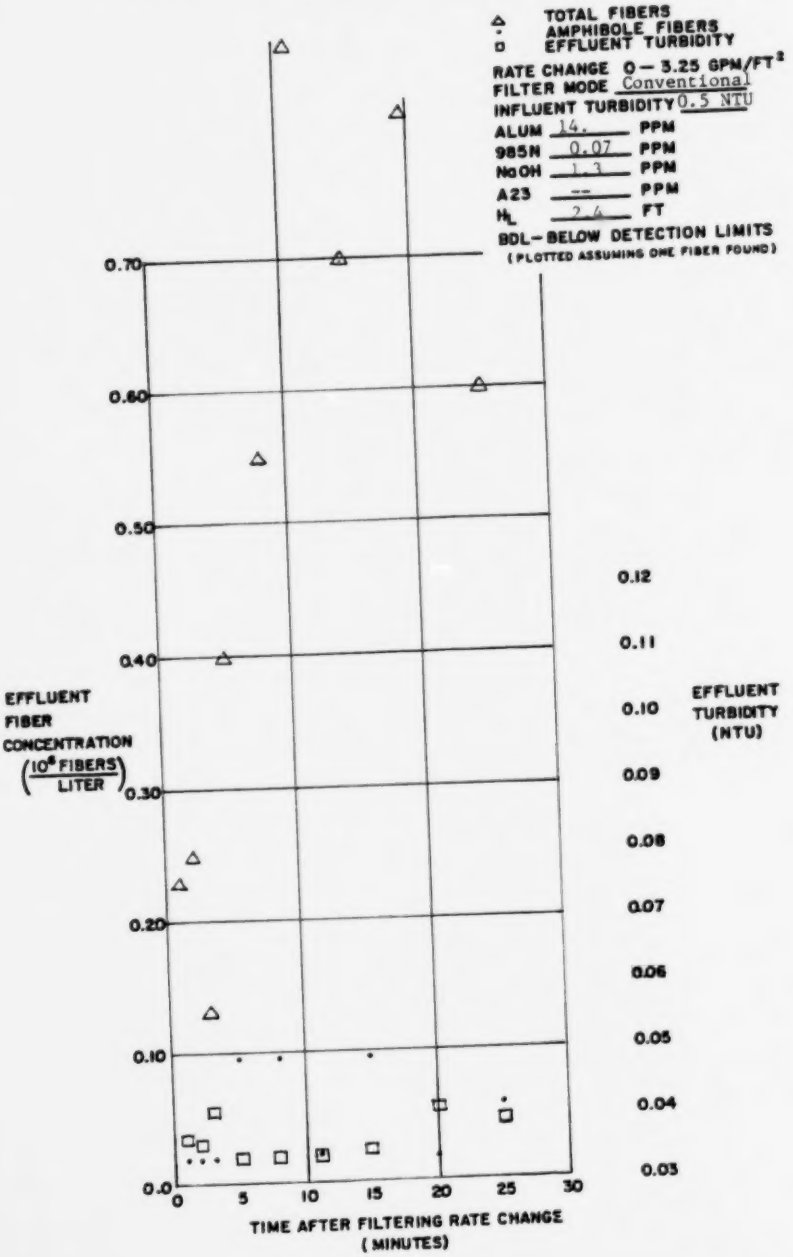
RUN 3 MARCH 6, 1978 FILTER NO. 1



GRAPH 37

CLEAN FILTER START-UP STRESS

RUN 4 MARCH 10, 1978 FILTER NO. 2

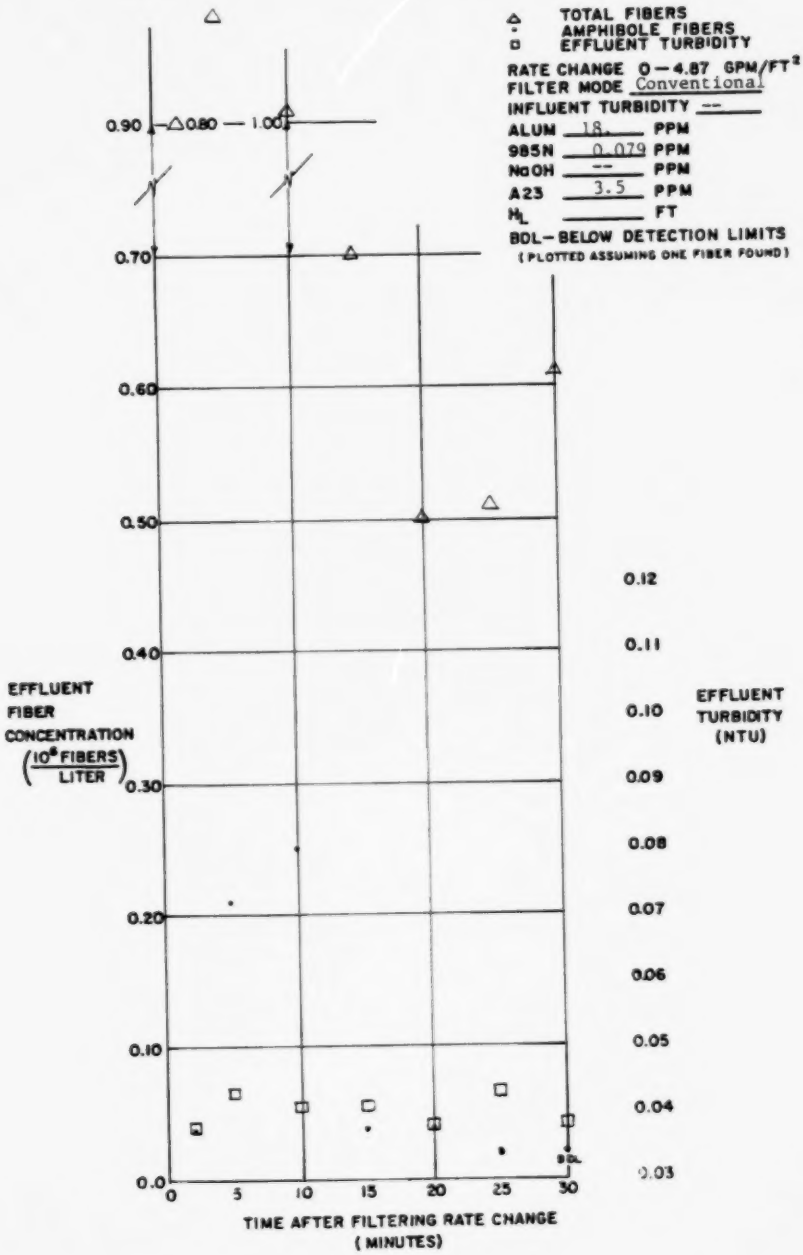


GRAPH 38

RUN 5

CLEAN FILTER START-UP STRESS

AUGUST 22, 1978 FILTER NO. 2

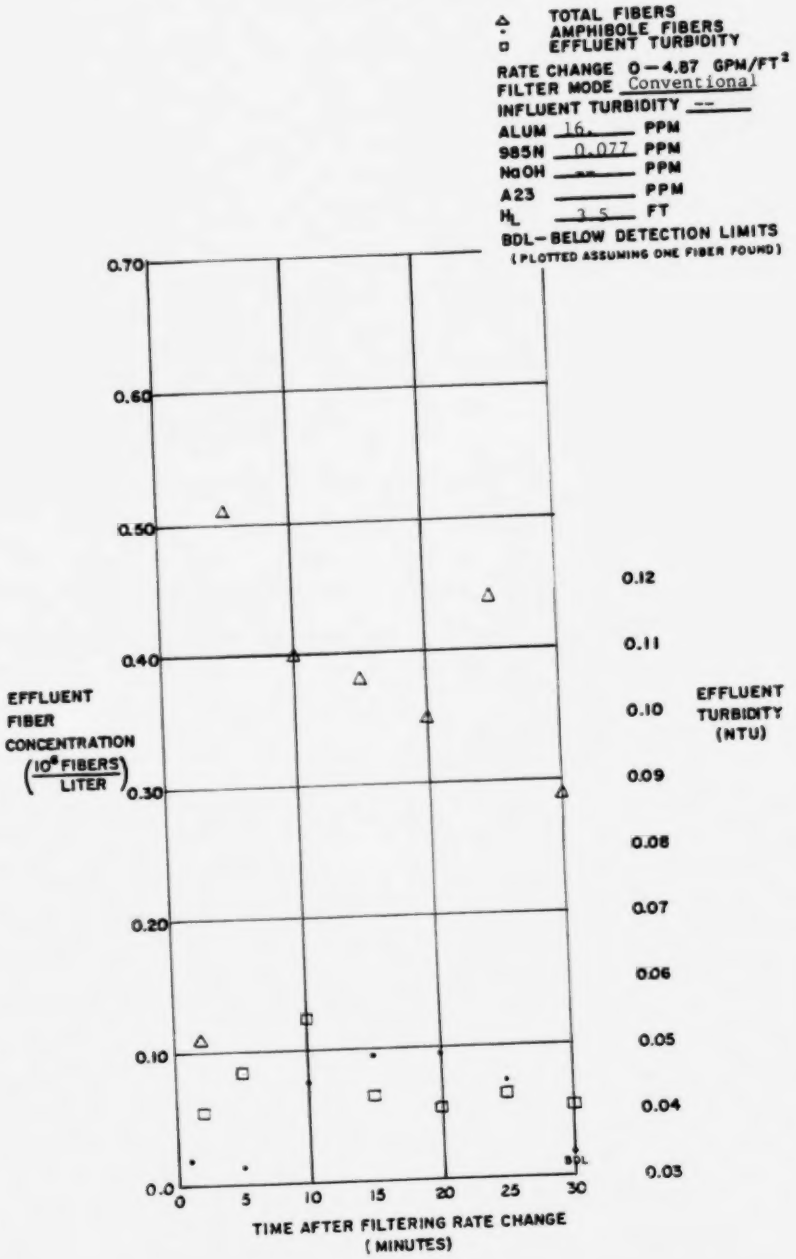


GRAPH 39

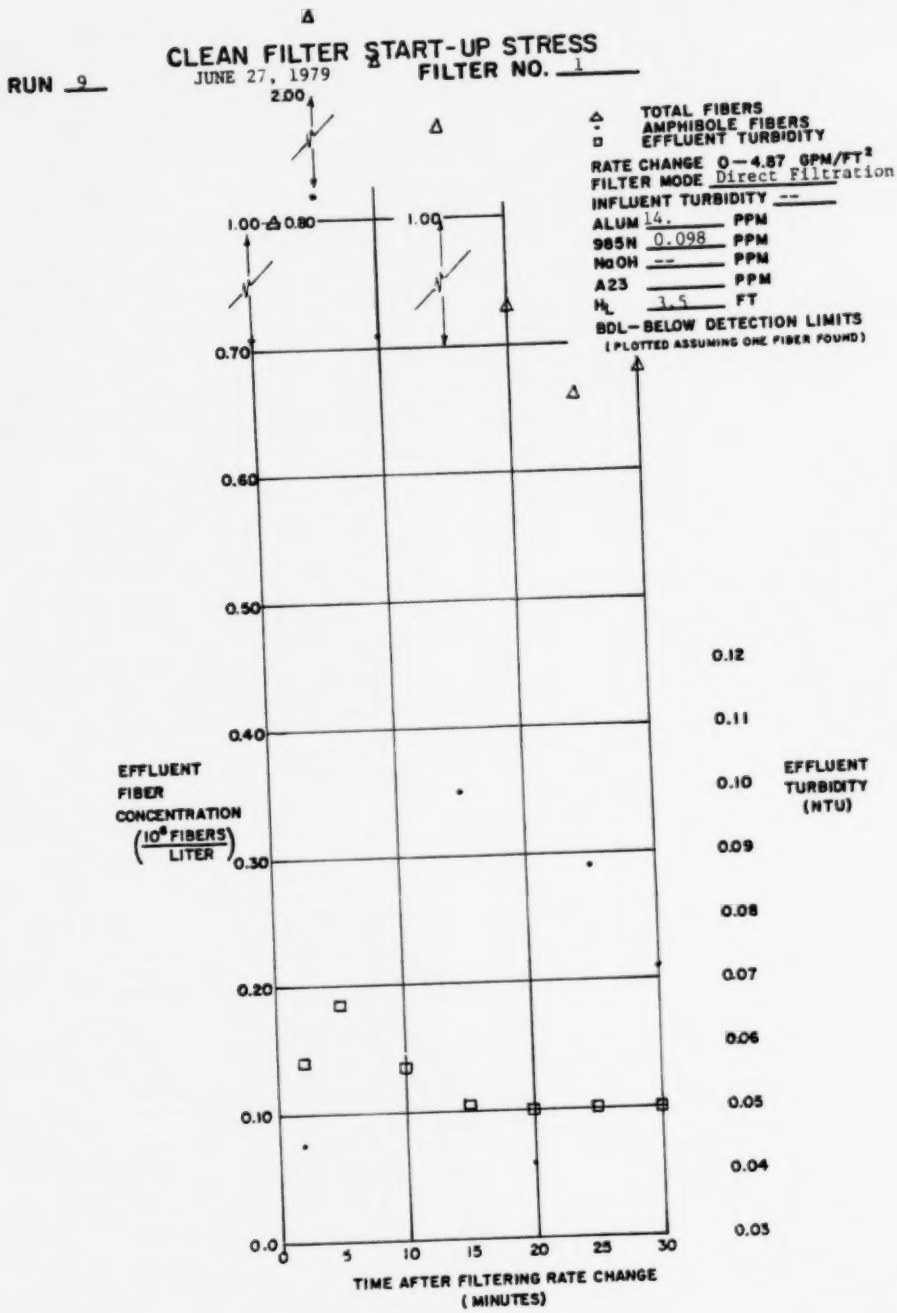
RUN 6

CLEAN FILTER START-UP STRESS

AUGUST 30, 1978 FILTER NO. 1



GRAPH 40


CLEAN FILTER START-UP STRESS
RUN 9
JUNE 27, 1979
FILTER NO. 1
TOTAL FIBERS
AMPHIBOLE FIBERS
EFFLUENT TURBIDITY
RATE CHANGE 0—4.87 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY --
ALUM 14. PPM
985N 0.098 PPM
NaOH -- PPM
A23 PPM
H_L 3.5 FT
BDL—BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)
EFFLUENT FIBER CONCENTRATION (10⁶ FIBERS / LITER)
EFFLUENT TURBIDITY (NTU)
TIME AFTER FILTERING RATE CHANGE (MINUTES)
2.00
1.00
0.80
1.00
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.0
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0
5
10
15
20
25
30

GRAPH 41

CLEAN FILTER START-UP STRESS

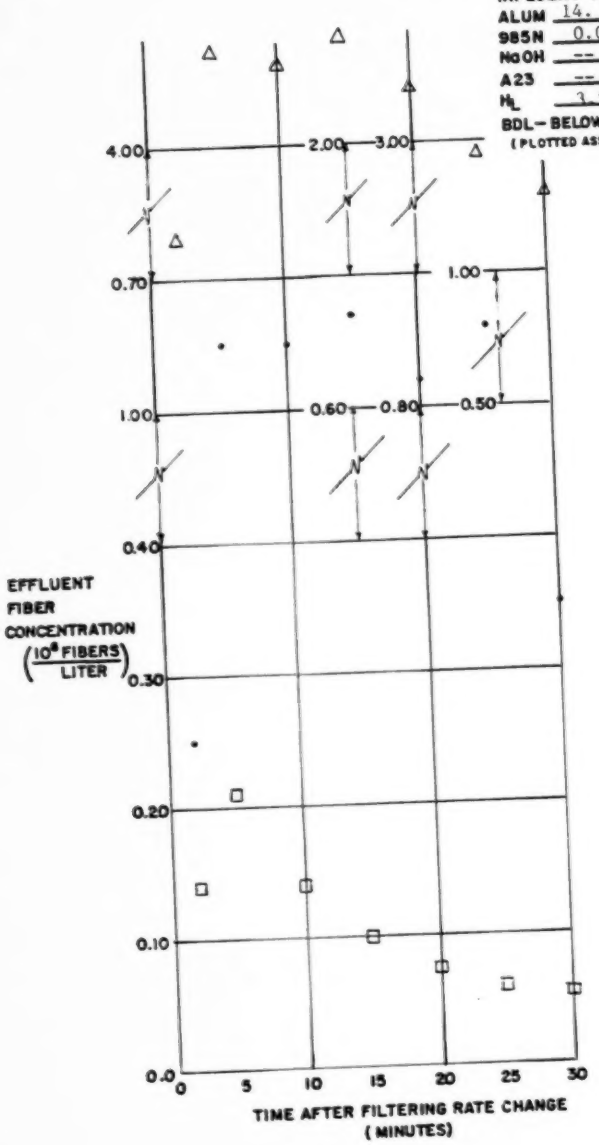
RUN 10

FILTER NO. 2

JUNE 27, 1979

△ TOTAL FIBERS
• AMPHIBOLE FIBERS
□ EFFLUENT TURBIDITY

RATE CHANGE 0 – 4.87 GPM/FT²
FILTER MODE Direct Filtration
INFLUENT TURBIDITY --
ALUM 14. PPM
985N 0.098 PPM
NaOH -- PPM
A23 -- PPM
H_L 3.5 FT
BDL – BELOW DETECTION LIMITS
(PLOTTED ASSUMING ONE FIBER FOUND)



GRAPH 42

APPENDIX D

FREEZE DEGREE DAYS

FREEZE DEGREE DAYS 1978-79

Total Freeze Degree Days: 3225

* Freeze Degree Days

	NOV	*	DEC		JAN		FEB		MAR	
Day	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)
1	44	-	0	32	-15	47	6	26	12	20
2	48	-	-5	37	-19	51	2	30	21	11
3	56	-	14	18	- 9	41	- 8	40	26	6
4	37	-	15	17	-16	48	-11	43	25	7
5	39	-	13	19	-15	47	-12	44	25	7
6	32	-	- 1	33	- 1	33	3	29	21	11
7	38	-	- 5	37	- 7	39	- 7	39	17	15
8	50	-	- 3	35	- 7	39	- 9	41	14	18
9	37	-	- 9	41	- 8	40	- 6	38	11	21
10	29	3	- 9	41	-16	48	-12	44	- 1	33
11	21	11	6	26	-20	52	4	28	18	14
12	24	8	26	6	1	31	- 1	33	17	15
13	32	0	15	17	- 6	38	- 5	37	25	7
14	24	8	18	14	-17	49	14	18	10	12
15	25	7	24	8	-11	43	4	28	6	26
16	24	8	21	11	-12	44	-16	48	27	5
17	29	3	19	13	0	32	-12	44	35	-
18	18	14	22	10	- 6	38	- 2	34	35	-
19	8	24	17	15	16	16	8	24	35	-
20	5	27	19	13	20	12	18	14	30	-
21	4	28	14	18	16	16	23	9	32	-
22	8	24	18	14	10	22	20	12	32	-
23	21	11	11	21	2	30	18	14	26	6
24	14	8	- 1	33	- 1	33	2	30	17	15
25	18	14	- 2	34	5	27	5	27	10	22
26	18	14	1	31	12	20	16	16	14	18
27	19	13	- 1	33	17	15	24	8	16	16
28	6	26	16	16	18	14	19	13	29	3
29	8	24	13	19	10	22			27	5
30	- 3	35	- 4	36	5	27			29	3
31			- 7	39	8	24			19	13
		310		737		1038		811		329

FREEZE DEGREE DAYS 1979-80

Total Freeze Degree Days: 1682.1

	NOV	*	DEC		JAN		FEB		MAR	
Day	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)
1	37	-	13.4	18.6	23.2	8.8	6.1	25.9	5.8	26.2
2	34	-	20.3	11.7	15.1	16.9	8.8	23.2	15.3	16.7
3	30	2	33.2	-	18.5	13.5	11.4	20.6	25.0	7
4	39	3	30.9	1.1	21.7	10.3	9.2	22.8	16.3	15.7
5	33	-	36	-	24.2	7.8	21.1	10.9	7.6	24.4
6	27	5	30.0	2	24.7	7.3	16.2	15.8	15.1	16.9
7	28	4	24.6	7.4	4.4	27.6	14.5	17.5	19.8	12.2
8	19	13	14.3	17.7	-12.6	44.6	20.4	11.6	23.3	8.7
9	16	16	30.5	1.5	-12.5	44.5	20.6	11.4	22.4	9.6
10	13	19	35.7	-	17.8	14.2	19.6	12.4	10.8	21.2
11	19	13	21.2	10.8	7.2	24.8	20.3	11.7	6.7	25.3
12	26	6	8.6	23.4	2.5	29.5	16.7	15.3	18.7	13.3
13	28	4	15.4	16.6	30.7	1.3	18.4	13.6	24.4	7.6
14	27	5	17.5	14.5	21.3	10.7	13.3	18.7	14.8	17.2
15	29	3	20.3	11.7	32.7	-	8.6	23.4	28.9	3.1
16	37	-	- 5.7	37.7	35.1	-	5.5	26.5	33.8	-
17	41	-	6.7	25.3	30.1	1.9	11.5	20.5	24	8
18	37	-	23.1	8.9	25.5	6.5	22.6	9.4	25.7	6.3
19	41	-	21.6	10.4	22.3	9.7	30.8	1.2	35.8	-
20	38.9	-	28.8	3.2	19.5	12.5	35.0	-	37.3	-
21	36.3	-	33.6	-	25.4	6.6	26.6	5.4	27.9	4.1
22	34.4	-	32.9	-	9.8	22.2	33.3	-	29.3	2.7
23	30.9	1.1	35.7	-	- 1.5	33.5	25.5	6.5		
24	29.3	2.7	30.1	1.9	12.3	19.7	16.7	15.3		
25	30.3	1.7	30	2	- 0.8	32.8	4.2	27.8		
26	36.9	-	29.3	2.7	- 5.6	37.6	13.3	18.7		
27	28.4	3.6	27.5	4.5	0.6	31.4	14.2	17.8		
28	25.8	6.2	27.5	4.5	2.2	29.8	5.0	27		
29	21.9	10.1	27.5	4.5	- 2.7	34.7	1.4	30.6		
30	14.8	17.2	32.2	-	5	27				
31			29.7	2.3	5.8	26.2				
		135.6		244.9		593.9		461.5		246.2

FREEZE DEGREE DAYS 1980-81

Total Freeze Degree Days: 1461.9 * Freeze Degree Days

	NOV	*	DEC		JAN		FEB		MAR	
Day	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)	T(°F)	F(°F)
1			14.6	17.4	18	14	13.2	18.8	28	4
2			11	21	- 2	34	- 6.3	38.3	21.4	10.6
3			24	8	-12.1	44.1	- 2	34	19.9	12.1
4			25.1	6.9	- 6.1	38.1	1.5	30.5	27.0	5.0
5			36.8	-	10.8	42.8	14.9	17.1	21.2	10.8
6			39.2	-	15	47	23.4	8.6	18.8	13.2
7			33.6	-	- 2.2	34.4	22.6	9.4	25.1	6.9
8			20.7	11.3	7.9	24.1	12.3	19.7	31.7	0.3
9			16.7	15.3	2.4	29.6	3.6	28.4	34.4	-
10			5.8	26.2	1.7	30.3	- 5.7	37.7	31.3	0.7
11			8.8	23.2	10	22	-12.1	44.1	34.7	-
12	35.5	-	22.7	9.3	19.3	12.7	- 3.2	35.2	38.7	-
13	34.7	-	14.4	17.6	19	13	2.4	29.6	30.1	1.9
14	30.7	1.3	16.5	15.5	14.5	17.5	18	14	41.2	-
15	28.8	3.2	22.5	9.5	9.4	22.6	35.2	-	37.6	-
16	30.0	2	28.9	3.1	11.2	20.8	40.8	-	40.2	-
17	27.8	4.2	30.1	1.9	25	7	39.2	-	29.8	2.2
18	28.2	3.8	13.8	18.2	26	6	40.6	-	26.1	5.9
19	39.3	-	- 3.1	35.1	18	14	33.8	-	29	3.0
20	37.5	-	- 0.5	32.5	28.6	3.4	34.4	-	33.7	-
21	36.0	-	16.7	15.3	30.1	1.9	34.1	-	31.1	0.9
22	43.7	-	26.4	5.6	34.1	-	35.9	-	32.4	-
23	31.5	.5	15.3	16.7	34.6	-	33.3	-	33.7	-
24	23.2	12.6	20.7	11.3	32.6	-	32.0	-		
25	26.1	5.9	3.2	28.8	35.7	-	27.6	4.4		
26	28.2	3.8	11.9	20.1	27.6	4.4	26.5	5.5		
27	33.2	-	23.8	8.2	14.9	17.1	28.8	3.2		
28	30.3	1.7	29.4	2.6	12.4	19.6	31.4	0.6		
29	33.2	-	17.8	14.2	8.0	24				
30	34	-	27.8	4.2	17.4	14.6				
31			29.6	2.4	26.1	5.9				
		39		401.4		564.9		379.1		77.5

FREEZE DEGREE DAYS 1981-82

Total Freeze Degree Days: 2959

	NOV		DEC		JAN		FEB		MAR	
Day	T(F)	F°Days	T(°F)	F°Days	T(°F)	F°Days	T(°F)	F°Days	T(°F)	F°Days
1	45	-	29	3	- 7	39	- 3	35	14	18
2	41	-	27	5	12	20	- 5	37	3	29
3	46	-	26	6	0	32	-17	49	- 5	37
4	52	-	21	11	- 4	36	-13	45	4	28
5	42	-	14	18	1	31	-19	51	8	24
6	34	-	26	6	-13	45	- 8	40	7	25
7	45	-	26	6	-16	48	4	28	- 5	37
8	33	-	21	11	-15	47	- 5	37	4	28
9	23		13	19	-27	59	-14	46	- 4	36
10	32	-	8	24	-20	52	- 7	39	20	12
11	31		19	13	- 5	37	3	29	18	14
12	41	-	25	7	- 6	38	4	28	25	7
13	44	-	22	10	- 4	36	6	26	27	5
14	39	-	8	24	- 8	40	16	16	24	8
15	39	-	2	30	-11	43	25	7	26	6
16	43	-	1	31	-28	60	22	10	30	2
17	31	1	- 2	34	-23	55	24	8	31	1
18	27	5	1	31	- 7	39	29	3	30	2
19	20	12	2	30	0	32	30	2	22	10
20	16	16	12	20	- 4	36	33	-	24	8
21	6	26	28	4	10	22	25	7	31	1
22	6	26	16	16	13	19	30	2	29	3
23	18	14	6	26	4	28	13	19	31	1
24	27	5	5	27	-13	45	8	24	27	5
25	28	4	8	24	- 9	41	2	30	20	12
26	29	3	15	17	- 1	33	17	15	10	22
27	23	9	18	14	20	12	18	14	8	24
28	21	11	6	26	7	25	23	9	28	4
29	22	10	- 2	34	6	26			36	-
30	25	7	0	32	- 1	33			36	-
31			3	29	-15	47			31	1
		149		588		1156		656		410

APPENDIX E

TEMPERATURES vs pH CURVES

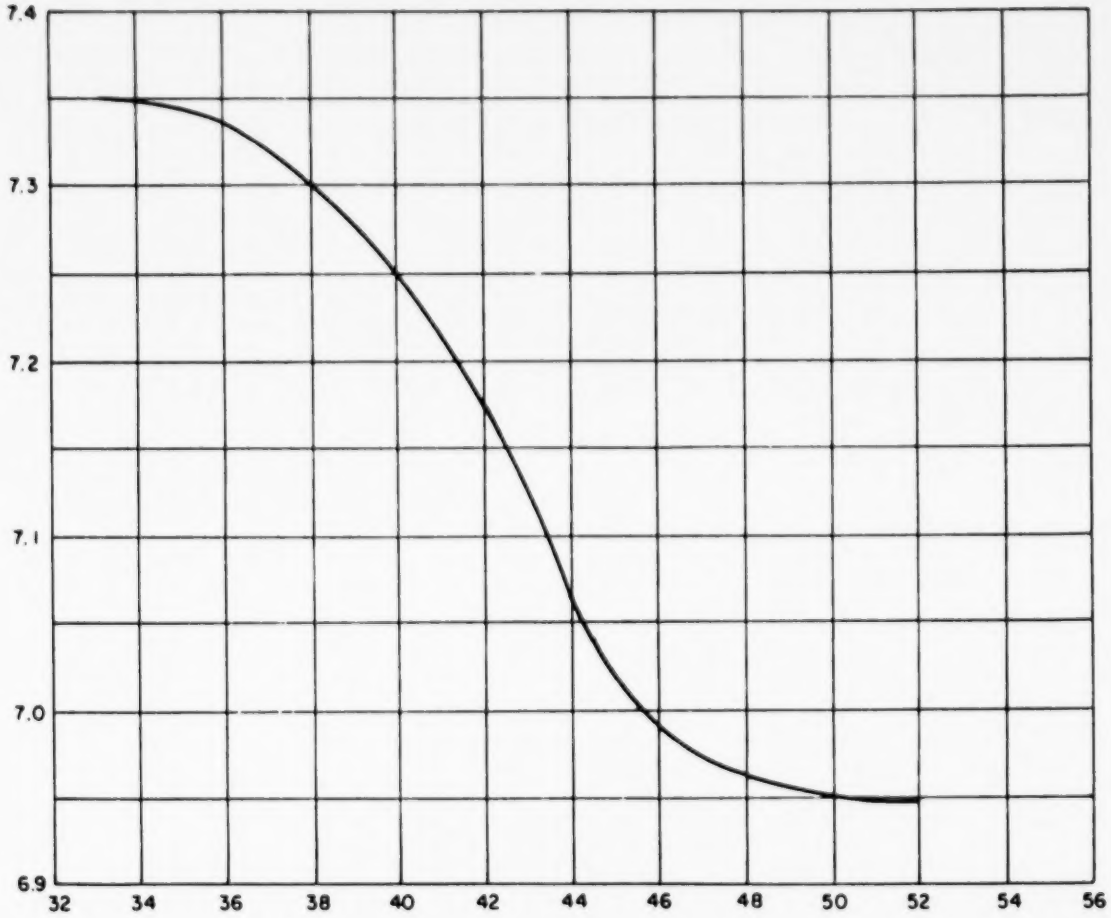


Figure 6 - Temperature vs pH - Cloquet Alum

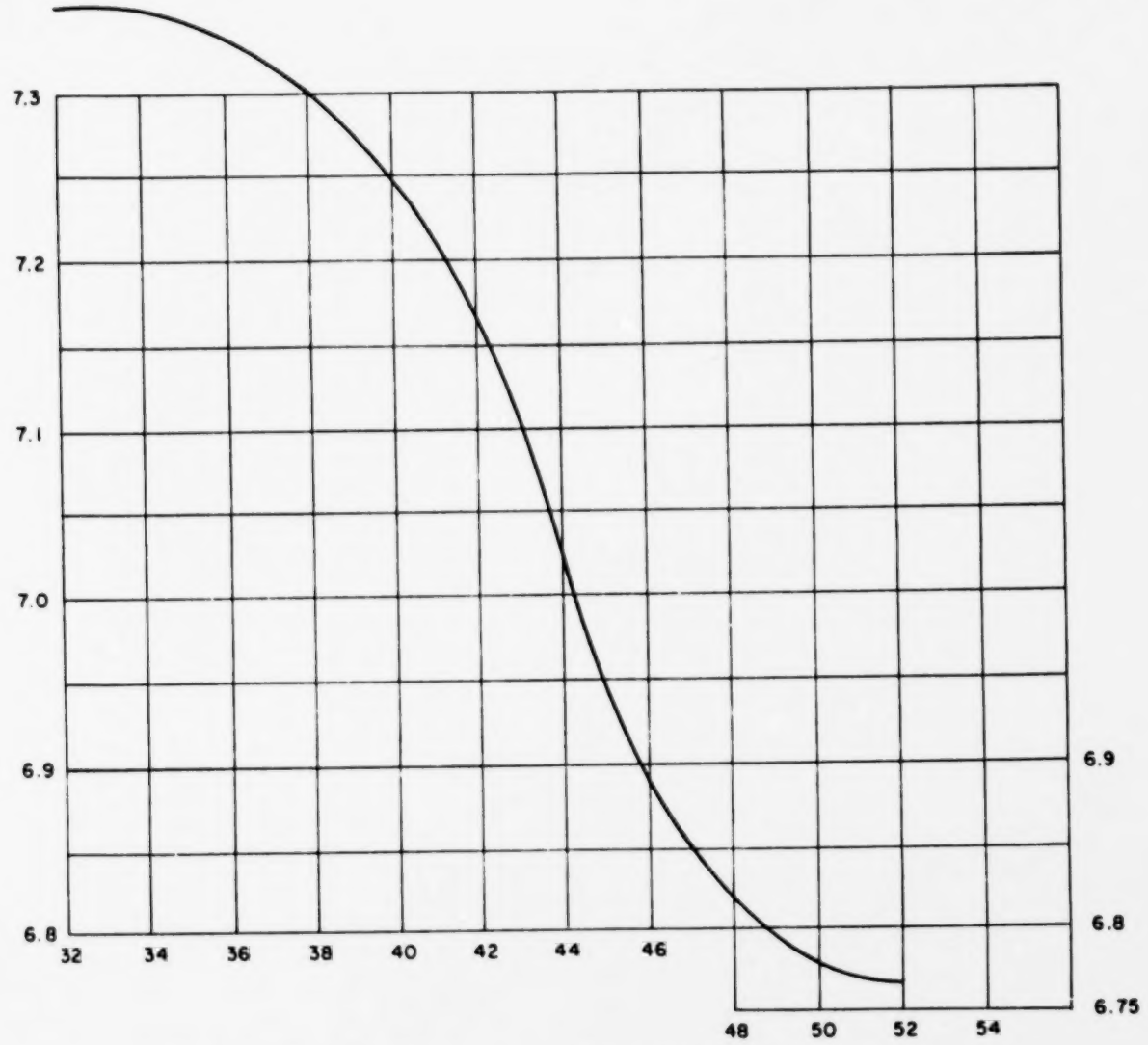


Figure 7 - Temperature vs pH - Non-Cloquet Alum